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The Weak (2, 2)-Labelling Problem for graphs with forbidden induced structures

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Abstract

The Weak (2, 2)-Conjecture is a graph labelling problem asking whether all connected graphs of at least three vertices can have their edges assigned red labels 1 and 2 and blue labels 1 and 2 so that any two adjacent vertices are distinguished either by their sums of incident red labels, or by their sums of incident blue labels. This problem emerged in a recent work aiming at proposing a general framework encapsulating several distinguishing labelling problems and notions, such as the well-known 1-2-3 Conjecture, a few of its variants, and so-called locally irregular decompositions. One further point of interest behind the Weak (2, 2)-Conjecture is that it is weaker than the 1-2-3 Conjecture, in the sense that the latter conjecture, if proved true, would imply the former one is true too.

In this work, we prove that the Weak (2, 2)-Conjecture holds for two classes of graphs defined in terms of forbidden induced structures, namely claw-free graphs and graphs with no pair of independent edges. One main point of interest for focusing on such classes of graphs is that the 1-2-3 Conjecture is not known to hold for them. Also, these two classes of graphs have unbounded chromatic number, while the 1-2-3 Conjecture is mostly understood for classes with bounded and low chromatic number.

Keywords: distinguishing labelling; 1-2-3 Conjecture; sum distinction.

1. Introduction

This work deals with several **distinguishing labelling problems**, taking part to a wide and vast area of research, as reported in several dedicated surveys on the topic, such as e.g. [7, 10]. More particularly, we focus on a subset of these problems revolving around the so-called **1-2-3 Conjecture**, which can all be defined through the following unified terminology, introduced recently in [4].

Let G be a graph, and $\alpha, \beta \geq 1$ be two positive integers. An (α, β) -labelling of G is an assignment ℓ of labels from $\{1, \dots, \alpha\} \times \{1, \dots, \beta\}$ to the edges of G , where each edge e gets assigned a *label* $\ell(e) = (x, y)$ with *colour* $x \in \{1, \dots, \alpha\}$ and *value* $y \in \{1, \dots, \beta\}$. Now, for every vertex v of G and any $i \in \{1, \dots, \alpha\}$, we denote by $\sigma_i(v)$ the *sum* of the values of the labels with colour i assigned to the edges incident to v , which we call the *i -sum* of v . We say that ℓ is *distinguishing* if for every two adjacent vertices u and v of G , there is an $i \in \{1, \dots, \alpha\}$ such that the i -sums of u and v differ, that is, if $\sigma_i(u) \neq \sigma_i(v)$.

Regarding these notions, it can be noted that if G is K_2 , the complete graph of order 2, then there are no $\alpha, \beta \geq 1$ such that G admits distinguishing (α, β) -labellings. This peculiar case apart, it is not too complicated to prove that, for any fixed $\alpha \geq 1$, there is a $\beta \geq 1$ such that distinguishing (α, β) -labellings of any graph G exist, and *vice versa*. For these reasons, in the context of distinguishing labellings, we generally focus on *nice graphs*, which

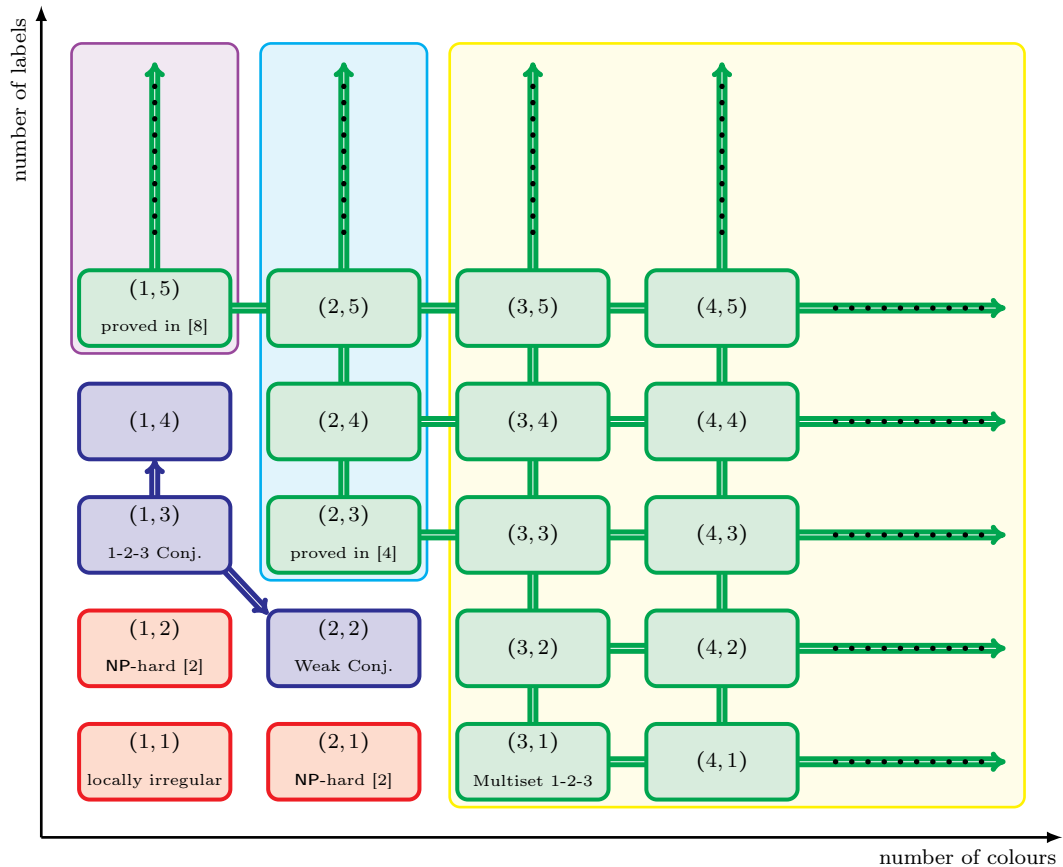


Figure 1: The current knowledge we have on whether all graphs admit distinguishing (α, β) -labellings, for fixed $\alpha, \beta \geq 1$. For a pair (α, β) , the associated box is green if all graphs were proved to admit the corresponding labellings, the associated box is red if it is known that not all graphs admit the corresponding labellings, while the associated box is blue if the status is currently unknown. Arrows indicate existential implications between pairs of types of labellings.

are those graphs with no connected component isomorphic to K_2 . Henceforth, throughout this work, every graph we consider is thus implicitly assumed nice.

A natural question, now, is whether, for some fixed $\alpha, \beta \geq 1$, every graph admits distinguishing (α, β) -labellings. It turns out, as mentioned earlier, that the literature actually provides answers for several values of α and β . See Figure 1 for a figure depicting our current knowledge on the topic, which we make more explicit below.

- Note first that if α, β and α', β' are values such that $\alpha' \geq \alpha$, $\beta' \geq \beta$, and $(\alpha, \beta) \neq (\alpha', \beta')$, then any distinguishing (α, β) -labelling is a distinguishing (α', β') -labelling.
- Distinguishing $(1, \beta)$ -labellings are labellings where all labels are of the same colour, and all adjacent vertices should be distinguished according to their sums of incident labels. Such labellings are exactly those behind the so-called 1-2-3 Conjecture [9] of Kalkowski, Karoński, and Pfender, which asks whether all graphs admit distinguishing $(1, 3)$ -labellings. To date, the best result towards this is that they all admit distinguishing $(1, 5)$ -labellings, see [8].
- Distinguishing $(\alpha, 1)$ -labellings can be seen as (improper) edge-colourings where, for every two adjacent vertices, there must be a colour that is not assigned the same number to their incident edges. These labellings are those defining the multiset

version of the 1-2-3 Conjecture, introduced in [1], which asks whether all graphs admit distinguishing $(3, 1)$ -labellings. This conjecture was proved in [11] by Vučković.

- In [4], the authors noticed that, given a distinguishing $(1, 5)$ -labelling of some graph, by modify the label colours and values in a particular fashion, we can derive a distinguishing $(2, 3)$ -labelling of the same graph. Similarly, there is a way, from a distinguishing $(1, 5)$ -labelling, to derive a distinguishing $(3, 2)$ -labelling.
- It is not too complicated to see that, in regular graphs, distinguishing $(1, 2)$ -labellings and distinguishing $(2, 1)$ -labellings are equivalent notions. In [2], it was proved that determining whether a given graph admits a distinguishing $(1, 2)$ -labellings is NP-hard. This means there exist infinitely many graphs that admit neither distinguishing $(1, 2)$ -labellings nor distinguishing $(2, 1)$ -labellings.
- Graphs admitting distinguishing $(1, 1)$ -labellings are precisely the so-called *locally irregular graphs*, which are those graphs with no two adjacent vertices having the same degree. These graphs have been appearing frequently in the field, and have even been receiving dedicated attention, see e.g. [5].

From this all, we arrive at the conclusion that there are only three pairs (α, β) for which we are still not sure whether all graphs admit distinguishing (α, β) -labellings: $(1, 3)$, which corresponds to the original 1-2-3 Conjecture; $(1, 4)$, which is weaker than the 1-2-3 Conjecture since more label values are available (while, similarly, all labels are of the same colour); and $(2, 2)$, which is the only pair for which we have two label colours to deal with. The latter pair leads to the following conjecture:

Weak $(2, 2)$ -Conjecture (Baudon *et al.* [4]). *Every graph admits a distinguishing $(2, 2)$ -labelling.*

At first glance, the 1-2-3 Conjecture and the Weak $(2, 2)$ -Conjecture might seem a bit distant. It is worth emphasising, however, that the former conjecture, if true, would imply the latter [6]. For this reason, the Weak $(2, 2)$ -Conjecture can be perceived as a weaker version of the 1-2-3 Conjecture. Also, to get progress towards these conjectures, one can thus investigate the Weak $(2, 2)$ -Conjecture for classes of graphs for which the 1-2-3 Conjecture is not known to hold. To date, the 1-2-3 Conjecture was mainly proved for 3-colourable graphs¹ [10]. The weaker conjecture was proved for 4-colourable graphs [6].

Theorem 1.1 (Bensmail [6]). *The Weak $(2, 2)$ -Conjecture holds for 4-colourable graphs.*

Both conjectures were also proved for other classes of graphs, but not as significant. One reason why the chromatic number parameter appears naturally in this context is that having a proper vertex-colouring ϕ in hands can be handy to design a distinguishing labelling, since ϕ informs on sets of vertices that are not required to be distinguished. One downside, however, is that making a labelling match ϕ somehow, might require lots of labels if ϕ itself contains lots of parts.

In this work, we prove the Weak $(2, 2)$ -Conjecture for two classes of graphs for which the 1-2-3 Conjecture is not known to hold. Furthermore, the two classes of graphs in question have unbounded chromatic number, which is significant according to the arguments above.

¹Recall that a *proper k -vertex-colouring* of a graph G is a partition of $V(G)$ into k independent sets. The *chromatic number* $\chi(G)$ of G is the smallest k such that G admits proper k -vertex-colourings. We say that G is *k -colourable* if $\chi(G) \leq k$, and *k -chromatic* if $\chi(G) = k$.

Precisely, we prove the Weak (2, 2)-Conjecture for $K_{1,3}$ -free graphs (graphs with no induced claw) and $2K_2$ -free graphs (graphs with no pair of independent edges). Both results are proved in a similar way: we first deal with the 5-colourable graphs of the class, before focusing on those with chromatic number at least 6.

This paper is organised as follows. In Section 2, we start off with some preliminaries, covering the terminology we use throughout, several lemmas, and previous results of interest. We then prove the Weak (2, 2)-Conjecture for $2K_2$ -graphs in Section 3, since the proof we give serves as a good introduction to the more technical proof, in Section 4, of the same result for $K_{1,3}$ -free graphs. We end this work in Section 5 with concluding words.

2. Preliminaries

Let G be a graph, and ℓ be a (α, β) -labelling of G . If $\alpha = 1$, then we will sometimes call ℓ a β -labelling for simplicity. Also, in such cases, instead of denoting the 1-sum of a vertex v by $\sigma_1(v)$, we will simply denote it as $\sigma(v)$, or as $\sigma_\ell(v)$ in case we want to emphasise that we refer to the labels assigned by ℓ . Now, in cases, where we are dealing with the Weak (2, 2)-Conjecture and, thus, $(\alpha, \beta) = (2, 2)$, it will more convenient to see the labels with colour 1 as *red labels*, and similarly those with colour 2 as *blue labels*. In this context, we will thus refer, for any vertex v , to the *red sum* $\sigma_r(v)$ of v (which is thus $\sigma_1(v)$), and to the *blue sum* $\sigma_b(v)$ of v (which is thus $\sigma_2(v)$).

In what follows, we point out situations where, assuming a partial labelling of a graph is given, we can extend it to some edges in such a way that some properties are preserved.

Lemma 2.1. *Let G be a graph, H be a connected bipartite subgraph of G , and ℓ be a partial 2-labelling of G such that only the edges of G are not labelled. For any vertex w of H , there is a 2-labelling ℓ' of H such that, for every two adjacent vertices u and v of H with $w \notin \{u, v\}$, we have*

$$\sigma_\ell(u) + \sigma_{\ell'}(u) \neq \sigma_\ell(v) + \sigma_{\ell'}(v).$$

Proof. Let U, V denote the bipartition of H . We produce such a 2-labelling ℓ' such that, for every vertex $u \neq w$ of H , we have $\sigma_\ell(u) + \sigma_{\ell'}(u) \equiv 0 \pmod{2}$ if $u \in U$, and $\sigma_\ell(u) + \sigma_{\ell'}(u) \equiv 1 \pmod{2}$ otherwise, if $u \in V$. Note that this clearly implies what we want to prove.

Start from all edges of H being assigned label 2 by ℓ' . Now, consider any vertex u of H for which $\sigma_\ell(u) + \sigma_{\ell'}(u)$ does not satisfy the required condition above. Since H is connected, there is a path P from u to w that uses edges of H only. Now turn all 1's assigned by ℓ' to the edges of P into 2's, and conversely turn all 2's into 1's. As a result, note that $\sigma_\ell(v) + \sigma_{\ell'}(v)$ is not altered for every vertex v of H with $v \notin \{u, w\}$, while both $\sigma_\ell(u) + \sigma_{\ell'}(u)$ and $\sigma_\ell(w) + \sigma_{\ell'}(w)$ had their parity altered. So $\sigma_\ell(u) + \sigma_{\ell'}(u)$ now verifies the desired condition.

Repeating those arguments until all vertices $u \neq w$ of H have $\sigma_\ell(u) + \sigma_{\ell'}(u)$ verifying the desired condition, we end up with ℓ' being as desired. \square

Building distinguishing labellings being nothing but an algebraic problem, there are contexts in which algebraic tools come up handy naturally. Below, we recall one such useful tool, and showcase a few ways to use it.

Theorem 2.2 (Combinatorial Nullstellensatz [3]). *Let \mathbb{F} be an arbitrary field, and $P = P(Z_1, \dots, Z_p)$ be a polynomial in $\mathbb{F}[Z_1, \dots, Z_p]$. Suppose that the coefficient of a monomial $Z_1^{k_1} \dots Z_p^{k_p}$, where every k_i is a non-negative integer, is non-zero in P and the degree of P equals $\sum_{i=1}^p k_i$. If S_1, \dots, S_p are subsets of \mathbb{F} with $|S_i| > k_i$ for every $i \in \{1, \dots, p\}$, then there are $z_1 \in S_1, \dots, z_p \in S_p$ so that $P(z_1, \dots, z_p) \neq 0$.*

Lemma 2.3. *Let G be a graph, H be a subgraph of G , and ℓ be a partial 2-labelling of G such that only the edges of H are not labelled. Then, there is a 2-labelling ℓ' of H such that, for every two adjacent vertices u and v of H , we have*

$$\sigma_\ell(u) + \sigma_{\ell'}(u) \neq \sigma_\ell(v) + \sigma_{\ell'}(v),$$

for H being any of:

- a path of length at least 2 not 3;
- a cycle with length multiple of 4.

Proof. Regarding the first case, assume H is a path $v_1 \dots v_p$ of length $p - 1 \geq 2$. For every $i \in \{1, \dots, p\}$, set $n_i = \sigma_\ell(v_i)$. Now, for every $i \in \{1, \dots, p - 1\}$, define e_i as the edge $v_i v_{i+1}$, and let Z_i be a variable belonging to $\{1, 2\}$ and representing any label assignment to e_i . We consider P , the polynomial defined as

$$P(Z_1, \dots, Z_{p-1}) = (n_1 - Z_2 - n_2) \cdot \prod_{i=2}^{p-2} (Z_{i-1} + n_i - Z_{i+1} - n_{i+1}) \cdot (Z_{p-2} + n_{p-1} - n_p).$$

Note that the degree of P is $p - 1$, and that the monomial $M = Z_1 \dots Z_{p-1}$ is thus of maximum degree. Note also that, since the n_i 's are fixed, the coefficient of M in the expansion of P is the same as the coefficient of the same monomial in the expansion of

$$P'(Z_1, \dots, Z_{p-1}) = (-Z_2) \cdot (Z_1 - Z_3) \cdot (Z_2 - Z_4) \cdot (Z_3 - Z_5) \cdots (Z_{p-3} - Z_{p-1}) \cdot (Z_{p-2}).$$

If $p \neq 4$, then $p - 2 \neq 2$. In this case, it can then be noted that there is only one way to form M by expending P' (due to the fact that the first factor contains Z_2 only, and that only the second one contains Z_1), and thus its coefficient is ± 1 . Thus M has non-zero coefficient. So the Combinatorial Nullstellensatz applies, and Theorem 2.2 implies we can assign labels from $\{1, 2\}$ to the edges of H so that, together with the labels by ℓ , the adjacent vertices of H are distinguished as desired.

Now consider the case where H is a cycle $v_0 \dots v_{p-1} v_0$ of length $p \equiv 0 \pmod{4}$. Again, for every $i \in \{0, \dots, p - 1\}$, set $n_i = \sigma_\ell(v_i)$, define e_i as the edge $v_i v_{i+1}$ (where the operation over the subscript is modulo p), and let Z_i be a variable belonging to $\{1, 2\}$ associated to e_i . We consider P , the polynomial

$$P(Z_0, \dots, Z_{p-1}) = \prod_{i=0}^{p-1} (Z_{i-1} + n_i - Z_{i+1} - n_{i+1}).$$

Since the n_i 's are constant, the coefficient of $M = Z_0 \dots Z_{p-1}$ in the expansion of P is the same as in that of

$$P'(Z_0, \dots, Z_{p-1}) = (Z_{p-1} - Z_1) \cdot (Z_0 - Z_2) \cdot (Z_1 - Z_3) \cdot (Z_2 - Z_4) \cdots (Z_{p-2} - Z_0).$$

Note that P' can be seen as

$$\prod_{\substack{i \text{ even} \\ 0 \leq i \leq p-2}} (Z_i - Z_{i+2}) \prod_{\substack{i \text{ odd} \\ 1 \leq i \leq p-3}} (Z_i - Z_{i+2}),$$

where the two involved products contain an even number of factors each ($p/2$), since $p \equiv 0 \pmod{4}$. From this, it is easy to see that the coefficient of $Z_0 Z_2 Z_4 \dots Z_{p-2}$ in the first product is 2, and similarly for the coefficient of $Z_1 Z_3 Z_5 \dots Z_{p-1}$ in the second product. Thus, the coefficient of M in P is 4, hence non-zero. Since M is of maximum degree, from the Combinatorial Nullstellensatz we get our conclusion here as well. \square

Lemma 2.4. *Let G be a graph, H be a subgraph of G isomorphic to a path $p_1p_2p_3p_4$ of length 3, and ℓ be a partial $(2,2)$ -labelling of G such that only the edges of H are not labelled. Assume also that the red sum of p_1 or p_4 by ℓ is at most 1, while it is 0 for p_2 and p_3 . Then, there is a $(2,2)$ -labelling ℓ' of H such that every two adjacent vertices of H are distinguished by their red sums by ℓ and ℓ' , or similarly by their blue sums by ℓ and ℓ' . Also, we can make sure that the red sum of any of $p_1, p_2, p_3,$ or p_4 is at most 1.*

Proof. If the red sum of both p_1 and p_4 by ℓ is 0, then we first assign red label 1 to p_2p_3 by ℓ' , before assigning blue label 1 to p_1p_2 , and blue label 2 to p_3p_4 . This way, p_1 and p_2 , and similarly p_4 and p_3 , are distinguished since the former vertex has red sum 0 while the latter has red sum 1. Also, p_2 and p_3 are distinguished since p_2 has blue sum 1 while p_3 has blue sum 2. We also have red sum at most 1 for all p_i 's.

If, say, p_1 has red sum 1 by ℓ , then note that, upon assigning blue labels by ℓ' to the edges of H , we cannot get any conflict between p_1 and p_2 , since they are distinguished by their red sums. In this case, a similar application of the Combinatorial Nullstellensatz as in the proof of Lemma 2.3 can be invoked to conclude that we can assign blue labels 1 and 2 by ℓ' to the edges of H to get the desired labelling. Denoting, for every $i \in \{1, 2\}$, by Z_i a variable in $\{1, 2\}$ corresponding to a blue label assigned to $p_i p_{i+1}$, note here that we can indeed restrict our attention to the polynomial $(Z_1 - Z_3)(Z_2)$, and more particularly to the monomial $Z_1 Z_2$, to get our conclusion.

Now, if both p_1 and p_4 have red sum 1 by ℓ , then, again, upon assigning blue labels to the edges of H by ℓ' , we cannot get any conflict between p_1 and p_2 , and similarly between p_4 and p_3 , since the former vertices have red sum 1 while the latter ones have red sum 0. So only p_2 and p_3 need to be distinguished, which can be done by assigning blue label 1 to p_1p_2 , blue label 2 to p_3p_4 , and any blue label to p_2p_3 . \square

Lemma 2.5. *Let G be a graph, H be a subgraph of G isomorphic to a cycle of even length, and ℓ be a partial $(2,2)$ -labelling of G such that only the edges of H are not labelled and all the edges of $E(G) \setminus E(H)$ are assigned red labels. Then, there is a $(2,2)$ -labelling ℓ' of H such that every two adjacent vertices of H are distinguished by their red sums by ℓ and ℓ' , or similarly by their blue sums by ℓ and ℓ' . Also, we can make sure that the blue sum of every vertex of H is at most 1.*

Proof. Assume H is a cycle of even length $k \geq 4$. We denote the consecutive vertices of H by $v_0 v_1 \dots v_{k-1} v_0$, and set $e_i = v_i v_{i+1}$ for every $i \in \{0, \dots, k-1\}$ (where all operations over the subscripts in this proof are modulo k).

Consider B , the subset of edges of H obtained as follows. We add e_1 to B , and, from here, we add every three edges of H , namely e_4, e_7 , and so on, to B , so that we add as many such edges to B as possible, but every two edges added to B are at distance at least 3 to each other in H . In particular, since $e_1 \in B$, neither e_0 nor e_{k-1} belongs to B . In particular, for every $e_i \in B$, we have $e_{i-1} \notin B$ and $e_{i+1} \notin B$, and for every $e_i, e_j \in B$ with $i \neq j$, we have $\{e_{i-1}, e_{i+1}\} \cap \{e_{j-1}, e_{j+1}\} = \emptyset$. Also, $H - B$, by how B was constructed, consists of paths P_1, \dots, P_p , all of which have length 2, but maybe one of them (the one containing v_0 , say it is P_p), which might be of length 2, 3, or 4.

By ℓ' , we start by assigning blue label 1 to all edges of B . In what follows, the edges of $E(H) \setminus B$ will all be assigned red labels. Note that these edges are precisely the edges of the P_i 's. Also, if $P_i = v_i v_{i+1} v_{i+2}$ is of length 2, then v_i and v_{i+2} are both incident to an edge of B , and thus are of blue sum 1, while v_{i+1} is of blue sum 0. Thus, when assigning red labels to the edges of the P_i 's, we only need to make sure to distinguish adjacent vertices v_i and v_{i+1} such that $v_i v_{i+1} \in B$, or v_i and v_{i+1} are inner vertices of P_p . Last, remark that if

$e_i \in B$, then, so that v_i and v_{i+1} are distinguished by their red sums, it suffices to make sure we assign red labels to e_{i-1} and e_{i+1} so that, when taking into account the contribution by ℓ , the red sums of v_i and v_{i+1} are of different parity.

We consider three distinct cases, involving the possible lengths of P_p :

- If P_p is of length 2, we are thus done when considering every $e_i \in B$ in turn, and assigning, by ℓ' , a red label to e_{i-1} and e_{i+1} so that, when taking into account the contribution by ℓ , the red sums of v_i and v_{i+1} are of different parity.
- Assume P_p is of length 3, *i.e.*, $P_p = v_{k-3}v_{k-2}v_{k-1}v_0$. In this case, we need to make sure that the red sums of v_{k-2} and v_{k-1} get different. To that end, we proceed as in the previous case, except that, when labelling e_0 and e_2 (to deal with $e_1 \in B$) and e_{k-5} and e_{k-3} (to deal with e_{k-4}), we do so so that the red sum of v_{k-2} , when taking into account the contribution by ℓ , becomes even, while that of v_{k-1} becomes odd.
- Similarly, if $P_p = v_{k-4}v_{k-3}v_{k-2}v_{k-1}v_0$ is of length 4, then we need to make sure that the red sums of v_{k-3} and v_{k-2} , and similarly of v_{k-2} and v_{k-1} , are different. This can be done by labelling e_{k-4} , e_{k-3} , e_{k-2} , e_{k-1} , and e_0 first, following that order, so that the desired pairs of adjacent vertices are distinguished due to their red sums having different parity. From here, we can again consider the edges in B and treat them at previously, taking into account, when dealing with e_1 and e_{k-4} , that e_0 and e_{k-4} have already been labelled.

This concludes the proof. □

To finish off, we recall a nice tool that proved to be very useful towards proving the multiset version of the 1-2-3 Conjecture from [1]. Let G be a graph. A *balanced tripartition* of G is a partition V_0, V_1, V_2 of $V(G)$ fulfilling, for every vertex $v \in V_i$ for any $i \in \{0, 1, 2\}$ (note that all operations over the subscripts are modulo 3), that $d_{V_{i+1}}(v) \geq \max\{1, d_{V_i}(v)\}$. That is, v has at least one neighbour in the next part V_{i+1} , and it actually has more neighbours in V_{i+1} than in V_i . It turns out that graphs with sufficiently large chromatic number admit such a balanced tripartition.

Theorem 2.6 (Addario-Berry *et al.* [1]). *Every graph G with $\chi(G) > 3$ admits a balanced tripartition.*

3. Graphs with no induced pair of independent edges

As mentioned earlier, we prove the Weak (2,2)-Conjecture for $2K_2$ -free graphs by first proving it for the 5-chromatic ones, and then for those with chromatic number at least 6. This implies the result, since the conjecture also holds for the 4-colourable ones, by Theorem 1.1. In what follows, we thus consider the two cases separately.

Theorem 3.1. *Every $2K_2$ -free graph with chromatic number 5 admits a distinguishing (2,2)-labelling.*

Proof. Let G be a $2K_2$ -free graph with chromatic number 5. We construct a distinguishing (2,2)-labelling of G assigning red labels 1 and 2 and blue labels 1 and 2. We can assume G is connected, since each of its 5-chromatic connected components can be handled through the arguments below, while Theorem 1.1 applies for its 4-colourable connected components.

Let D be a maximal independent set of G , and set $\mathcal{R} = G - D$. Note that every vertex v in \mathcal{R} is incident to at least one *upward edge* vu , *i.e.*, going to D (so, $u \in D$). We say

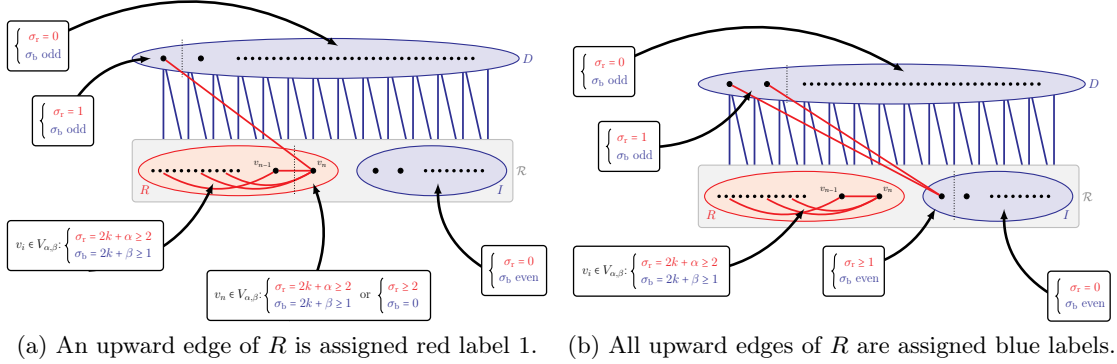


Figure 2: Terminology used in the proof of Theorem 3.1, and the red sums and blue sums we aim at getting for the vertices by the designed $(2, 2)$ -labelling. (a) and (b) depict the two main cases we consider.

that a connected component of \mathcal{R} is *empty* if it contains no edges, while it is *non-empty* otherwise. Since G is $2K_2$ -free, note that \mathcal{R} contains at most one non-empty connected component. Actually, \mathcal{R} must contain exactly one non-empty connected component R as otherwise G would be bipartite, contradicting that its chromatic number is 5. Let now I denote the vertices from the empty connected components of \mathcal{R} , and let \mathcal{H} be the subgraph of G induced by the edges incident to the vertices of I . Then \mathcal{H} is bipartite, and, again, because G is $2K_2$ -free, it must be that \mathcal{H} consists of only one connected component.

Since G is 5-chromatic, note that R is 4-chromatic; let thus $V_{0,0}, V_{0,1}, V_{1,0}, V_{1,1}$ be parts forming a proper 4-vertex-colouring ϕ of R . We modify ϕ , if needed, so that if v is a vertex of R with $d_R(v) = 1$, then v belongs to $V_{0,0}$ or $V_{0,1}$ (note that this is clearly possible, since v has exactly one neighbour in R). Now order the vertices v_1, \dots, v_n in any way satisfying that, for every $i \in \{1, \dots, n-1\}$, vertex v_i is incident to at least one *forward edge* $v_i v_j$ (*i.e.*, with $j > i$, which is a *backward edge* from v_j 's point of view). Such an ordering can be obtained e.g. by reversing the ordering in which vertices are encountered while performing a breadth-first search algorithm from any vertex (standing as the last vertex v_n).

We are now ready to start labelling the edges of G . We begin with all edges incident to the vertices of R . We consider the v_i 's one by one, following the ordering above, and for every vertex v_i considered in that course, we assign a label to all upward edges (assigning them blue labels, except in one peculiar case) and forward edges (assigning them red labels only) incident to v_i so that some desired red sum and blue sum are realised at v_i . When proceeding that way, note that, whenever considering a new vertex as v_i , only its backward edges can be assumed to be labelled, with red labels. The procedure goes as follows:

- If $i \neq n$, then v_i is incident to forward edges. We start by assigning blue label 2 to all upward edges incident to v_i , and red label 2 to all forward edges incident to v_i . Assume $v_i \in V_{\alpha,\beta}$. If $\sigma_b(v_i) \not\equiv \beta \pmod{2}$, then we change to blue label 1 the label assigned to any one upward edge incident to v_i . Likewise, if $\sigma_r(v_i) \not\equiv \alpha \pmod{2}$, then we change to red label 1 the label assigned to any one forward edge incident to v_i . This way, we get $\sigma_r(v_i) \equiv \alpha \pmod{2}$ and $\sigma_b(v_i) \equiv \beta \pmod{2}$. In particular, by how we modified ϕ earlier, note that we must have $\sigma_r(v_i) \geq 2$ (either $d_R(v_i) \geq 2$ in which case this condition clearly holds; or $d_R(v_i) = 1$, in which case $\alpha = 0$ and thus the only inner edge incident to v_i is assigned red label 2, implying the condition).
- If $i = n$, then the only edges incident to v_n that remain to be labelled are upward edges. Recall, in particular, that all backward edges incident to v_n are assigned red labels. We consider two cases, assuming $v_n \in V_{\alpha,\beta}$:

- If $\sigma_r(v_n) \equiv \alpha \pmod{0}$, then we assign blue labels to all upward edges incident to v_n , their values being chosen so that $\sigma_b(v_n) \equiv \beta \pmod{0}$. In that case, we thus have $\sigma_r(v_n) \equiv \alpha \pmod{2}$ and $\sigma_b(v_n) \equiv \beta \pmod{2}$. Again, by how ϕ was modified earlier, we must have $\sigma_r(v_n) \geq 2$.
- If $\sigma_r(v_n) \not\equiv \alpha \pmod{0}$, then we assign red label 1 to any one upward edge incident to v_n , while we assign blue labels to the others upward edges (if any) so that $\sigma_b(v_n) \equiv \beta \pmod{2}$. In this case, either $\sigma_b(v_n) \neq 0$ in which case $\sigma_r(v_n) \equiv \alpha \pmod{2}$ and $\sigma_b(v_n) \equiv \beta \pmod{2}$; or $\sigma_b(v_n) = 0$ in which case all edges incident to v_n are assigned red labels (implying that $\sigma_r(v_n) \geq 2$).

Note that, in all cases above, for all vertices $v_i \in V_{\alpha,\beta}$, we guarantee $2 \leq \sigma_r(v_i) \equiv \alpha \pmod{2}$. Also, except maybe for v_n , we also guarantee $0 < \sigma_b(v_i) \equiv \beta \pmod{2}$. Regarding v_n , either $\sigma_b(v_n) = 0$, in which case v_n is distinguished from all its neighbours in R through its blue sum, or $0 < \sigma_b(v_n) \equiv \beta \pmod{2}$, in which case v_n is distinguished from its neighbours in R through its red sum. Regarding the vertices of D , only one of them can currently be incident to an edge being assigned a red label, and, if this is the case, then it is incident to exactly one such edge, being assigned red label 1. So, for every $u \in D$, we currently have $\sigma_r(u) \leq 1$, while $\sigma_r(v) \geq 2$ for every $v \in R$. Thus, currently, vertices of R are distinguished from their neighbours in D . If \mathcal{H} has no edges, then all edges of G are actually labelled, and we end up with a distinguishing $(2,2)$ -labelling. So, in what follows, we can assume \mathcal{H} has edges.

We are now left with labelling the edges of \mathcal{H} , which, recall, consists of exactly one connected component. We consider two main cases:

- Assume there is some vertex $w \in \mathcal{H}$ with $\sigma_r(w) = 1$. Recall that there can be only one such vertex, which belongs to D and must be a neighbour of v_n . Recall also that the vertices of $D \cap V(\mathcal{H})$ can be incident to edges being currently assigned blue labels (being upward edges incident to vertices of R). Taking these labels into account, by Lemma 2.1 we can assign blue labels 1 and 2 to the edges of \mathcal{H} so that any two of its adjacent vertices u and v with $w \notin \{u, v\}$ are distinguished by their blue sums.

Since we did not modify labels assigned to edges incident to the vertices in R , and the edges of \mathcal{H} are assigned blue labels only, the vertices of R remain distinguished from their neighbours due to arguments above. Regarding adjacent vertices of \mathcal{H} , they are either distinguished by their blue sums (if w is not involved), or because one of them has red sum 1 (if w is involved). So, here as well, we do not have conflicts.

- Assume no vertex of \mathcal{H} currently has red sum at least 1. In this case, let w be any vertex of I . By Lemma 2.1, we can assign blue labels 1 and 2 to the edges of \mathcal{H} so that, taking into account the other edges of G that are currently already assigned blue labels, and omitting w , any two adjacent vertices of \mathcal{H} are distinguished by their blue sums. In case w has $d \geq 2$ neighbours x_1, \dots, x_d (which lie in D), then we further modify the labelling by changing to red label 1 the label assigned to wx_1, \dots, wx_d .

Again, we did not modified the red sums and blue sums of the vertices in R . Also, the only vertex of $D \cup I$ that might have red sum at least 2 is w (note that the x_i 's, if they exist, have red sum 1), which lies in I , the set of isolated vertices of \mathcal{R} , and thus cannot be adjacent to the vertices of R . Since the vertices of R have red sum at least 2, they thus cannot be involved in conflicts. Now, if $d_G(w) = 1$, then, because G is not just an edge, the unique neighbour of w must have degree at least 2, meaning that w is distinguished from its unique neighbour by its blue sum. Otherwise, *i.e.*, w

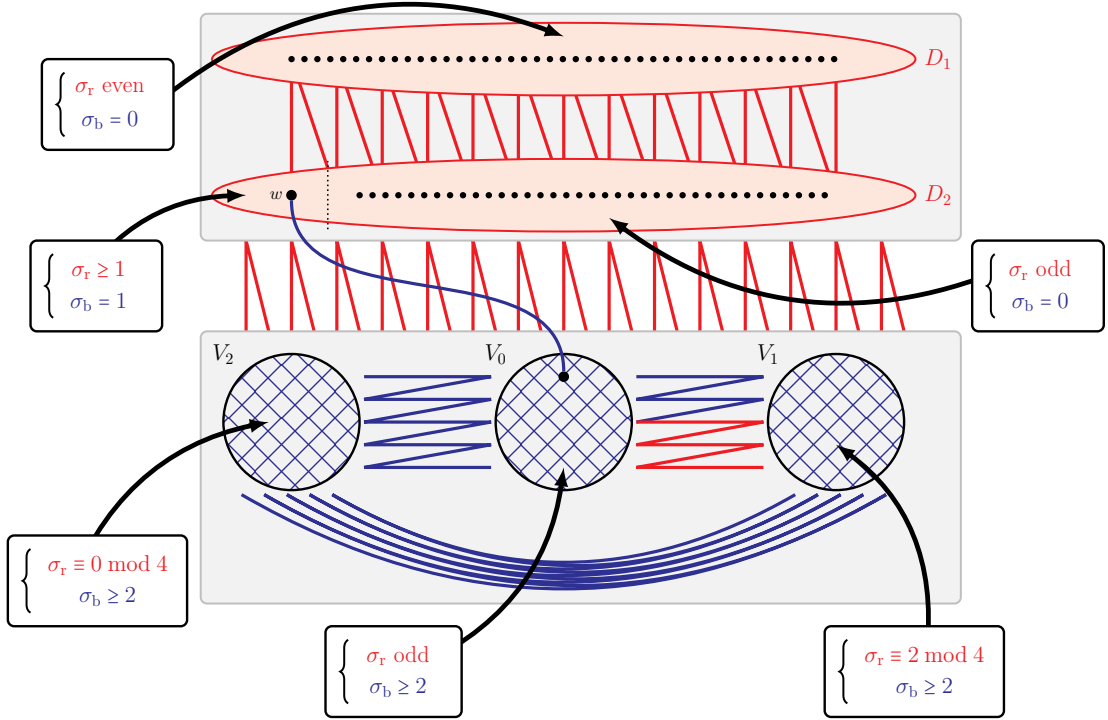


Figure 3: Terminology used in the proof of Theorem 3.2, and the red sums and blue sums we aim at getting for the vertices by the designed $(2, 2)$ -labelling.

has $d \geq 2$ neighbours $x_1, \dots, x_d \in D$, then $\sigma_r(w) = d \geq 2$ while the x_i 's have red sum 1, and thus w cannot be involved in conflicts. Regarding the x_i 's, they have red sum 1, so they cannot be in conflict with their neighbours of \mathcal{H} different from w , since they have red sum 0. Finally, for every vertex of \mathcal{H} not in $\{w, x_1, \dots, x_d\}$, note that we did not modify its blue sum when perhaps introducing red labels. Then we still have that any two such adjacent vertices are distinguished by their blue sums, due to how we applied Lemma 2.1. So, no conflicts exist in G .

In both cases, the resulting $(2, 2)$ -labelling of G is thus distinguishing, as desired. \square

Theorem 3.2. *Every $2K_2$ -free graph with chromatic number at least 6 admits a distinguishing $(2, 2)$ -labelling.*

Proof. Let G be a $2K_2$ -free graph with chromatic number at least 6. We construct a distinguishing labelling of G assigning red labels 1 and 2 and blue labels 1 and 2. Note that we may assume that G is connected, due to Theorems 1.1 and 3.1.

Let D_1 be a maximal independent set of G . Note that every vertex of $G - D_1$ has at least one neighbour in D_1 . Now let D_2 be a maximal independent set of $G - D_1$. Similarly, every vertex of $G - D_1 - D_2$ has at least one neighbour in D_2 . Since $\chi(G) \geq 6$, note that $\chi(G - D_1 - D_2) \geq 4$. According to Lemma 2.6, there is thus a balanced tripartition V_0, V_1, V_2 of $G - D_1 - D_2$. Note that $D_1, D_2, V_0, V_1,$ and V_2 form a partition of $V(G)$. An *upward edge* of G is an edge with one end in $V_0 \cup V_1 \cup V_2$ and the other in $D_1 \cup D_2$. An *inner edge* of G is an edge with both ends in some V_i . If $u \in V_i$ and $u' \in V_{i+1}$ (where the operations over the subscripts of the V_i 's are modulo 3) are adjacent for some $i \in \{0, 1, 2\}$, then uu' is a *forward edge* from u 's perspective, and a *backward edge* from that of u' . Because G

is $2K_2$ -free, note that all three of $G[V_0]$, $G[V_1]$, and $G[V_2]$ contain exactly one connected component each.

We denote by \mathcal{H} the set of the connected components of $G[D_1 \cup D_2]$. Since every vertex of D_2 has neighbours in D_1 , note that \mathcal{H} has edges. Actually, since G is $2K_2$ -free, there is exactly one connected component H of \mathcal{H} that is *non-empty*, *i.e.*, that contains edges. \mathcal{H} can also contain *empty* connected components, which consist in a single vertex of D_1 .

We design the desired $(2, 2)$ -labelling of G following four steps. First, we label all inner, upward, and forward edges incident to the vertices of V_0 so that they fulfil certain properties on σ_r and σ_b . Second and third, we then achieve the same for the vertices of V_1 and V_2 . During a fourth and last step, we label the remaining edges of \mathcal{H} (if any).

Step 1: Labelling the inner, upward, and forward edges incident to V_0 .

We start by labelling the following edges of G :

1. We first assign blue label 2 to all inner edges incident to vertices of V_0 .
2. Then consider every vertex u of V_0 in turn, assign red label 2 to all upward edges incident to u , and, if needed, eventually change to red label 1 one of these red labels so that the red sum of u becomes odd.
3. We now distinguish two cases, through which we get to defining a special vertex $w \in D_2$ that will be useful later on, by the last step of the proof.
 - $|V_0| = 1$, *i.e.*, $G[V_0]$ is a single vertex u . We here assign blue label 2 to all forward edges incident to u . We also modify the labelling further as follows. Set w as any neighbour of u in D_2 . Note that, by swapping the red labels assigned to uw and another upward edge incident to u , we can, if necessary, assume uw is assigned red label 2. We then change the label assigned to uw to blue label 1.
 - Otherwise, *i.e.* $|V_0| \geq 2$. Here, let u_1, \dots, u_n be an arbitrary ordering over the vertices of V_0 , and consider the u_i 's one by one in order. Since extra modifications must be made around u_1 , let us consider that vertex specifically before describing the general case. Just as in the previous case, let w be any neighbour of u_1 in D_2 . Again, we can swap labels assigned to upward edges, if necessary, so that u_1w is assigned red label 2. Then we change the label assigned to u_1w to blue label 1, before assigning blue label 2 to all forward edges incident to u_1 . Now, for every subsequent u_i with $i \geq 2$, denote by u_{i_1}, \dots, u_{i_d} the $d \geq 0$ neighbours of u_i in V_0 that precede u_i in the ordering. If $d = 0$, then assign blue label 2 to all forward edges incident to u_i . Now, if $d \geq 1$, then recall that u_i is incident to at least d forward edges. By assigning red label 2 to none, one, two, etc., or all of these edges, and blue label 2 to all others, we can increase the red sum of u_i by any amount in $\{0, 2, \dots, 2d\}$, which set contains $d + 1$ elements. There is thus a way to assign red label 2 to at most d forward edges incident to u_i , and blue label 2 to the rest, so that the red sum of u_i is different from the red sums of u_{i_1}, \dots, u_{i_d} .

Once the steps above have been performed fully, note that all inner, upward, and forward edges incident to the vertices of V_0 are assigned a label. Also, for every vertex $u \in V_0$, we currently have $\sigma_r(u) \equiv 1 \pmod{2}$, and it can be checked that also $\sigma_b(u) \geq 2$. Furthermore, every two adjacent vertices of V_0 currently have their red sums being different. Remark last that all upward edges incident to the vertices of V_0 are assigned red labels, except for w , which is incident to exactly one edge assigned blue label 1.

Step 2: Labelling the inner, upward, and forward edges incident to V_1 .

Due to the previous step, note also that all backward edges incident to the vertices in V_1 are labelled with red label 2 and blue label 2. So, one should keep in mind that, currently, $\sigma_r(u)$ is even for every $u \in V_1$.

We now label more edges as follows:

1. First, we assign blue label 2 to all inner edges incident to vertices of V_1 .
2. Second, we consider every vertex u of V_1 in turn. Recall that u is incident to at least two upward edges. We assign red label 2 to all these edges. If necessary, we change the label assigned to two of these edges to red label 1, so that $\sigma_r(u) \equiv 2 \pmod{4}$.
3. Third, let u_1, \dots, u_n be an arbitrary ordering over the vertices of V_1 , and consider the u_i 's one by one in turn. For every u_i considered that way, denote by u_{i_1}, \dots, u_{i_d} the $d \geq 0$ neighbours of u_i in V_1 that precede u_i in the ordering. If $d = 0$, then assign blue label 2 to all forward edges incident to u_i . Now, if $d \geq 1$, then recall that u_i is incident to at least d forward edges. Thus, through assigning blue labels to these edges, we can make the blue sum of u_i vary by any amount in the set $\{d, \dots, 2d\}$, which contains $d+1$ elements. Thus, it is possible to assign blue labels to the forward edges incident to u_i so that its resulting blue sum is different from that of u_{i_1}, \dots, u_{i_d} .

After completing the previous steps, all edges incident to the vertices in V_1 are labelled. For every vertex $u \in V_1$, we get $\sigma_r(u) \equiv 2 \pmod{4}$, and also $\sigma_b(u) \geq 2$, because either $d_{V_1}(u) = 0$ and at least one forward edge incident to u is assigned blue label 2, or $d_{V_1}(u) > 0$ and at least one inner edge incident to u is assigned blue label 2. Also, every two adjacent vertices of V_1 are distinguished by their blue sums. Note last that all upward edges incident to the vertices of V_1 are assigned red labels.

Step 3: Labelling the inner, upward, and forward edges incident to V_2 .

Note that after performing the previous step, all backward edges incident to the vertices of V_2 are assigned blue labels, meaning that their red sum is currently 0.

We now perform the following:

1. We assign blue label 2 to all inner edges incident to vertices in V_2 .
2. We then consider every vertex u of V_2 in turn, which, recall, is incident to at least two upward edges. We assign red label 2 to all these edges before, if necessary, changing the label assigned to two of these edges to red label 1, so that $\sigma_r(u) \equiv 0 \pmod{4}$.
3. We finish off this step similarly as the previous one. let u_1, \dots, u_n be any ordering over the vertices of V_2 , and consider the u_i 's one after the other. For every u_i , let u_{i_1}, \dots, u_{i_d} be the $d \geq 0$ neighbours of u_i in V_2 that precede u_i in the ordering. If $d = 0$, then assign blue label 2 to all forward edges incident to u_i . Otherwise, if $d \geq 1$, then recall that u_i is incident to at least d forward edges. Via assigning blue labels to these edges, we can thus make the blue sum of u_i increase by any value in $\{d, \dots, 2d\}$, which set contains $d+1$ elements. Thus, we can assign blue labels to the forward edges incident to u_i so that its blue sum is different from that of u_{i_1}, \dots, u_{i_d} .

Once this step achieves, all edges incident to vertices in $V_0 \cup V_1 \cup V_2$ are labelled. For every vertex $u \in V_2$, we have $\sigma_r(u) \equiv 0 \pmod{4}$ and $\sigma_b(u) \geq 2$. Every two adjacent vertices of V_2 are distinguished by their blue sums, while all upward edges incident to the vertices

in V_2 are assigned red labels. It is important to emphasise also that assigning blue labels to the edges joining vertices of V_2 and V_0 altered the blue sums of the vertices in V_0 , which is not an issue since the adjacent vertices of V_0 are distinguished by their red sums, which were not altered. So, any two adjacent vertices in V_0 remain distinguished, and similarly for any two adjacent vertices in V_1 . Finally, note that any two adjacent vertices in distinct V_i 's are distinguished by their red sums having different values modulo 4.

Step 4: Labelling the edges of \mathcal{H} .

Recall that, at this point, we have $\sigma_b(v) = 0$ for every vertex $v \in D_1 \cup D_2 \setminus \{w\}$ and $\sigma_b(w) = 1$, while $\sigma_b(u) \geq 2$ for every vertex $u \in V_0 \cup V_1 \cup V_2$. In particular, if $v \in D_1$ belong to an empty connected component of \mathcal{H} , then all edges incident to v are already labelled, and v is distinguished from its neighbours due to its blue sum.

Recall that H denotes the unique non-empty connected component of \mathcal{H} , and that H actually contains all edges of G that remain to be labelled. Recall also that H contains w , a special vertex we defined in the first labelling step, which is the only vertex of H having non-zero blue sum. According to Lemma 2.1, we can assign red labels 1 and 2 to the edges of H so that, even when taking into account the red labels assigned to the upward edges incident to the vertices in $V_0 \cup V_1 \cup V_2$, any two adjacent vertices of H different from w are distinguished by their red sums. Since $\sigma_b(w) = 1$ while $\sigma_b(v) = 0$ for every $v \in V(\mathcal{H})$, vertex w is also distinguished from its neighbours in \mathcal{H} . These conditions guarantee we have not introduced any conflicts involving vertices of $D_1 \cup D_2$ and vertices of $V_0 \cup V_1 \cup V_2$.

All these arguments imply that the resulting $(2, 2)$ -labelling of G is distinguishing. \square

4. Graphs with no induced claw

We now prove the Weak $(2, 2)$ -Conjecture for $K_{1,3}$ -free graphs. Again, we do so by first focusing on the 5-chromatic ones, before focusing on those with chromatic number at least 6. Again, we consider the two cases separately.

Theorem 4.1. *Every claw-free graph with chromatic number 5 admits a distinguishing $(2, 2)$ -labelling.*

Proof. The proof starts similarly as that of Theorem 3.1. We can assume G is a connected 5-chromatic graph. We again define D and \mathcal{R} as previously, as well as the 4-vertex-colouring ϕ of \mathcal{R} with parts $V_{0,0}$, $V_{0,1}$, $V_{1,0}$, and $V_{1,1}$. The notions of empty and non-empty connected components of \mathcal{R} are also defined similarly, as well as the classification of the edges of G into upward and inner edges. The set I and the subgraph \mathcal{H} are also defined similarly.

Some differences here, however, are because G is claw-free. Note in particular that \mathcal{R} might contain several non-empty connected components. However, any vertex v of \mathcal{R} has at most two neighbours in D , and conversely any vertex $u \in D$ can have neighbours in at most two connected components of \mathcal{R} . Also, \mathcal{H} can now have several connected components containing edges. As will be pointed out, further strong assumptions on \mathcal{H} can be made.

Similarly as in the proof of Theorem 3.1, we start by considering every non-empty connected component R of \mathcal{R} , and defining a particular ordering over its vertices. In some cases, we also modify the parts of ϕ by a bit.

- If R has a vertex v with $d_R(v) = 2$, then we denote the vertices of R by v_1, \dots, v_n in reverse order as they are encountered during a breadth-first search algorithm performed from v . So, $v = v_n$, and every $v_i \neq v_n$ is incident to a forward edge, which is a backward edge from the other vertex's point of view.

Regarding ϕ , denoting by v_i and v_j the two neighbours of v_n , we need to make sure that we do not have v_i in $V_{0,0}$ and v_j in $V_{0,1}$ (or *vice versa*), or v_i in $V_{1,0}$ and v_j in $V_{1,1}$ (or *vice versa*). That is, if $v_i \in V_{\alpha,\beta}$ and $v_j \in V_{\alpha',\beta'}$, we need $\alpha \neq \alpha'$. Assume this is not verified, and that we have, w.l.o.g., v_i in $V_{0,0}$ and v_j in $V_{0,1}$. Then, since ϕ is proper, v_n belongs to $V_{1,0}$ or $V_{1,1}$. Assume v_n belongs to $V_{1,0}$, w.l.o.g. We modify ϕ by swapping the parts $V_{0,1}$ and $V_{1,0}$. Note that the resulting ϕ remains proper, and that, now, v_i still lies in $V_{0,0}$, while v_j lies in $V_{1,0}$, as desired.

Finally, if R has a vertex v_i with $d_R(v_i) = 1$, then, keeping ϕ proper, we make sure that v_i lies in $V_{0,0}$ or $V_{0,1}$.

- If R has no degree-2 vertex but has a vertex v with degree 1, *i.e.*, $d_R(v) = 1$, then we denote by v_1, \dots, v_n the vertices of R as in the previous case, *i.e.*, from a breadth-first search algorithm performed from $v = v_n$. In this case as well, we also modify ϕ , if needed, so that all the degree-1 vertices of R belong to $V_{0,0} \cup V_{0,1}$.
- If R has minimum degree 3, then we consider any vertex v of R , and denote by v_1, \dots, v_n the vertices of R as in the previous cases (by reversing a breadth-first search algorithm performed from v), so that $v_n = v$. Here, ϕ is not modified further.

We are now ready to start designing the (2,2)-labelling of G . Just as in the proof of Theorem 3.1, we start by labelling all edges incident to vertices in the non-empty connected components of \mathcal{R} , so that every two of their adjacent vertices are distinguished either by their red sums or by their blue sums. To achieve this, we will assign red labels to all inner edges and blue labels to most upward edges, so that the red sums and blue sums obtained for the vertices in \mathcal{R} match ϕ . By that, we mean that for every vertex v in $V_{\alpha,\beta}$, we aim at getting $\sigma_r(v) \equiv \alpha \pmod{2}$ and $\sigma_b(v) \equiv \beta \pmod{2}$, except in a few cases (such as for some last vertices of some non-empty connected components).

Consider every non-empty connected component $R \in \mathcal{R}$ in turn. Recall that v_1, \dots, v_n is an ordering over the vertices of R with specific properties we described earlier. We consider the v_i 's one by one following the ordering, and, whenever considering a v_i in this way, we assign a label to all its incident inner edges and upward edges. This way, note that, whenever starting treating a v_i , only its incident backward edges are labelled.

Now, for every $v_i \in V_{\alpha,\beta}$ to be considered:

- If $i \neq n$, then v_i is incident to forward edges. We first assign blue label 2 to all upward edges incident to v_i , and red label 2 to all incident forward edges. Note that all edges incident to v_i are now assigned a label. Now, if $\sigma_b(v_i) \not\equiv \beta \pmod{2}$, then we change to blue label 1 the label assigned to any upward edge incident to v_i . Similarly, if $\sigma_r(v_i) \not\equiv \alpha \pmod{2}$, then we change to red label 1 the label assigned to any forward edge incident to v_i . As a result, $\sigma_r(v_i) \equiv \alpha \pmod{2}$ and $\sigma_b(v_i) \equiv \beta \pmod{2}$. Recall also that if $d_R(v_i) = 1$, then $\alpha = 0$, and thus $\sigma_r(v_i) \geq 2$. Since all inner edges incident to v_i are assigned red labels, we also have $\sigma_r(v_i) \geq 2$ whenever $d_R(v_i) \geq 2$. Thus, $\sigma_r(v_i) \geq 2$ regardless of $d_R(v_i)$. Also, $\sigma_b(v_i) \geq 1$.
- If $i = n$, then all inner edges incident to v_n are currently assigned red labels.
 - If $d_R(v_n) = 2$, then recall that, due to how we ordered the vertices of R , the two neighbours v_j and v'_j of v_n in R have their red sums being of distinct parity. Assume that, currently, $\sigma_r(v_n) \equiv \sigma_r(v_j) \pmod{2}$ and $\sigma_r(v_n) \not\equiv \sigma_r(v'_j) \pmod{2}$. We here assign blue labels to all upward edges incident to v_n , their values being chosen so that $\sigma_b(v_n) \not\equiv \sigma_b(v_j) \pmod{2}$. For the sake of formality, we also change,

if needed, the part of ϕ that contains v_n , so that the part it belongs to matches the resulting $\sigma_r(v_n)$ and $\sigma_b(v_n)$.

- If $d_R(v_n) = 1$ and R is just an edge v_1v_2 (thus with $v_2 = v_n$), then, by how ϕ was modified earlier (v_1 and v_2 belong to $V_{0,0} \cup V_{0,1}$), recall that v_1v_2 must be assigned red label 2. We here assign blue labels to the upward edges incident to v_n so that $\sigma_b(v_1) \not\equiv \sigma_b(v_2) \pmod{2}$.
- Otherwise, *i.e.*, $d_R(v_n) = 1$ and R is not just an edge, or $d_R(v_n) \geq 3$, then we assign red label 1 to all upward edges incident to v_n .

Once the process above is led for all v_i 's, all edges incident to the v_i 's are labelled. Also, if $v_i \in V_{\alpha,\beta}$ for some $i < n$, then $\sigma_r(v_i) \equiv \alpha \pmod{2}$ and $\sigma_b(v_i) \equiv \beta \pmod{2}$ with $\sigma_r(v_i), \sigma_b(v_i) \geq 1$. Since ϕ is a proper vertex-colouring, for every two adjacent vertices v_i and v_j of R with $i, j \neq n$, we thus have $\sigma_r(v_i) \neq \sigma_r(v_j)$ or $\sigma_b(v_i) \neq \sigma_b(v_j)$. Regarding v_n , either v_n is not in conflict with any of its neighbours in R (with respect to either σ_r or σ_b) and none of its incident upward edges is assigned a red label (when $d_R(v_n) = 2$, or $d_R(v_n) = 1$ with R being an edge), or all its incident edges are assigned red labels and thus $\sigma_b(v_n) = 0$ (while all neighbours v_j of v_n in R have $\sigma_b(v_j) \geq 1$).

At this point, only edges incident to the vertices in I remain to be labelled. Later on, these edges will be assigned blue labels only. This means that, through labelling these edges, the red sums of the vertices in D will not be modified. Recall that the vertices in D might be incident to edges assigned red labels. We need to make sure that such vertices will not be in conflict with the vertices from the non-empty connected components of \mathcal{R} .

Let u be any vertex in D . Note that, by how we labelled the upward edges earlier, if v_iu is an edge assigned a red label, then v_iu is assigned red label 1, and $i = n$, *i.e.*, v_i is the last vertex of its non-empty connected component of \mathcal{R} . Since G is claw-free, this means u must be incident to at most two edges assigned a red label. Thus, currently, $\sigma_r(u) \leq 2$. Meanwhile, for every vertex v in a non-empty connected component of \mathcal{R} , we have $\sigma_r(v) \geq 2$. Hence, if $\sigma_r(u) = \sigma_r(v)$, then $\sigma_r(u) = 2$.

In what follows, we modify the current labelling, if needed, so that there are no two adjacent vertices $u \in D$ and $v \in V(\mathcal{R})$ with $\sigma_r(u) = \sigma_r(v) = 2$, without introducing new conflicts between adjacent vertices of \mathcal{R} . To achieve this, we perform label modifications to make the number of such conflicts decrease, until no such conflict remains. We perform this so that, for every $v \in V(\mathcal{R})$, we preserve, except in very peculiar cases, $\sigma_r(v) \geq 2$ while, for every $u \in D$, we have $\sigma_r(u) \leq 2$. This way, no conflicts between the vertices of D and $V(\mathcal{R})$ will remain.

Assume there is a $u \in D$ with $\sigma_r(u) = 2$. As mentioned earlier, there are thus exactly two edges uv_n and uv'_n incident to u assigned red label 1, where v_n is the last vertex of some non-empty connected component R of \mathcal{R} , and v'_n is the last vertex of another non-empty connected component $R' \neq R$ of \mathcal{R} . Assume that u is adjacent to a vertex v_i from a non-empty connected component of \mathcal{R} with the same red sum (possibly, $v_i \in \{v_n, v'_n\}$). Then $\sigma_r(v_i) = 2$, and, since all edges of \mathcal{R} are assigned red labels, $d_R(v_i) \leq 2$.

- Assume $\sigma_r(u) = \sigma_r(v_i)$ for some $v_i \notin \{v_n, v'_n\}$. Recall that v_iu is assigned a blue label. Also, because G is claw-free, v_i must belong to the same (non-empty) connected component of \mathcal{R} as one of v_n and v'_n . Assume v_i belongs to R . Then, v_iv_n is an edge.
 - If $d_R(v_i) = 1$, then, by how the vertices of R were ordered, $d_R(v_n) \leq 2$.
 - * If $d_R(v_n) = 1$, then R is actually just the edge $v_iv_n = v_1v_2$. By how we treated v_n earlier, recall that all upward edges incident to v_n are assigned blue labels. So, this case cannot occur.

- * If $d_R(v_n) = 2$, then, by how we treated v_n earlier, it cannot be that $v_n u$ is assigned a red label. Thus, this case cannot occur as well.
- Assume now that $d_R(v_i) = 2$. Then, again, by how the vertices of R were ordered, it must be that $d_R(v_n) = 2$, and no upward edge incident to v_n is actually assigned a red label. So, again, this case cannot occur.
- Assume now that $\sigma_r(u) = \sigma_r(v_n)$, w.l.o.g., and that there is no $v_i \in V(R) \cup V(R') \setminus \{v_n, v'_n\}$ such that $\sigma_r(u) = \sigma_r(v_i)$ (that is, the previous case does not apply). Since $v_n u$ is assigned red label 1, note that, in order to have $\sigma_r(v_n) = 2$ with upward edges incident to v_n being assigned red labels, it must be that v_n is incident to exactly one inner edge $v_j v_n$ (that is, $d_R(v_n) = 1$) and to the one upward edge $v_n u$. So, $d_G(v_n) = 2$. Furthermore, $v_j v_n$ is assigned red label 1, while we also assigned red label 1 to $v_n u$. Also, by our choice of v_n and by how we treated R , we have $d_R(v_j) \geq 3$

- If $d_G(u) \geq 3$, then note that, regardless of how the edges incident to u that are not the two assigned red label 1 are labelled, we will eventually not have any conflict between u and v_n , and can thus leave things as is.
- Assume now $d_G(u) = 2$. Regarding v'_n , the fact that we had to assign red label 1 to $v'_n u$ means (by previous arguments) that $d_{R'}(v'_n) \neq 2$, and that if $d_{R'}(v'_n) = 1$ then R' is not just an edge. Actually, all edges incident to v'_n are assigned red labels. If $\sigma_r(v'_n) \neq \sigma_r(u)$ (that is, if $\sigma_r(v'_n) > \sigma_r(u)$), then we change the label assigned to $v'_n u$ to red label 2. This way, we get $\sigma_r(u) = 3 > 2 = \sigma_r(v_n)$, and we thus got rid of the conflict between v_n and u . Meanwhile, we still have $\sigma_r(v'_n) > \sigma_r(u)$ while $\sigma_r(v'_n) \geq 3$ and $\sigma_b(v'_n) = 0$, while all neighbours of v'_n in R' have blue sum at least 1. So, v'_n cannot be involved in a conflict.

The last case is thus when also $\sigma_r(v'_n) = \sigma_r(u) = 2$, which, for similar reasons as for v_n , occurs when $d_{R'}(v'_n) = 1$, the only inner edge incident to v'_n is assigned red label 1, and $v'_n u$ is the only upward edge incident to v'_n , which is assigned red label 1. So, $d_G(v'_n) = 2$. In this case, we are done when changing the label assigned to $v_n u$ and $v'_n u$ to red label 2. As a result, $\sigma_r(v_n) = \sigma_r(v'_n) = 3$ while $\sigma_r(u) = 4$. Meanwhile, we still have $\sigma_b(v_n) = \sigma_b(v'_n) = 0$, while u is the only neighbour of v_n and v'_n with blue sum 0.

It now remains to label edges incident to the vertices in I . Recall that \mathcal{H} is the subgraph of G induced by these edges. Then \mathcal{H} is bipartite. In particular, since G is claw-free, in every connected component H of \mathcal{H} , every vertex must be of degree at most 2. So H must be a path, or an even-length cycle. Actually, if H is an even-length cycle $u_1 v_1 \dots u_k v_k u_1$ (where the u_i 's belong to D and the v_i 's belong to I), then note that every u_i cannot have another neighbour in G , *i.e.*, in a non-empty connected component of \mathcal{R} , because, since G is claw-free, this would imply that one of its neighbours in H must be adjacent to a vertex from a non-empty connected component of \mathcal{R} , a contradiction. So, all connected components of \mathcal{H} must be paths. Besides, if H is a path of \mathcal{H} , then, due to the claw-freeness of G , every degree-2 vertex of H must also be a degree-2 vertex in G .

Now let H be a connected component of \mathcal{H} , *i.e.*, a path. If H has length 1, then $H = u_1 v_1$ where $u_1 \in D$ and $v_1 \in I$, meaning that $d_G(v_1) = 1$, and, because G is connected and is not a one-edge graph, whatever labelling we consider, it must be that u_1 and v_1 are distinguished either by their red sums or by their blue sums. So assume now H has length more than 1. Set $H = w_1 \dots w_k$ with $k \geq 3$. Now, for every $i \in \{1, \dots, k\}$, denote by n_i the current value of $\sigma_b(w_i)$. Possibly, $n_i = 0$. Actually, recall that only n_1 and n_k can

be non-zero. According to Lemma 2.3 or 2.4, it is possible to assign blue labels 1 and 2 to the edges of H so that its adjacent vertices are distinguished by their blue sums.

Since we have not altered the red sums of the vertices of \mathcal{R} , every two adjacent vertices of \mathcal{R} remain distinguished, and similarly for any two adjacent vertices from \mathcal{R} and D (in particular, the only vertices of D which had their red sums modified have red sum 1, while the vertices of \mathcal{R} still have red sum at least 2). Regarding the adjacent vertices of \mathcal{H} , the application of Lemma 2.3 or 2.4 guarantees that they are distinguished by their blue sums, or by their red sums in certain cases. So, the resulting labelling of G is distinguishing. \square

Theorem 4.2. *Every claw-free graph with chromatic number at least 6 admits a distinguishing $(2, 2)$ -labelling.*

Proof. The proof starts similarly as that of Theorem 3.2. Again, we can assume G is a claw-free graph with chromatic number at least 6. We again start from two maximal independent sets D_1 and D_2 , chosen consecutively, and define \mathcal{H} as $G[D_1 \cup D_2]$. For the current proof, we classify the connected components of \mathcal{H} into three groups. That is, a connected component $H \in \mathcal{H}$ is *empty* if it contains no edges, *bad* if it consists of one edge only, and *nice* otherwise, *i.e.*, if it contains at least two edges. Since all vertices in $V(G) \setminus D_1$ have at least one neighbour in D_1 , note that if H is empty, then its only vertex belongs to D_1 . Meanwhile, if H is bad, then it consists of one vertex in D_1 and one in D_2 .

Before going on, we need to add a last constraint on the choice of D_1 and D_2 . Namely, among all possible choices as D_1 and D_2 , we choose one that minimises the number of empty connected components in \mathcal{H} . Under this hypothesis, we derive the following property:

Claim 4.3. *If $u \in V(G) \setminus (D_1 \cup D_2)$ is adjacent to an isolated vertex $v_1 \in D_1$, then u must be adjacent to two vertices $v'_1 \in D_1$ and $v_2 \in D_2$ such that $v'_1 v_2$ is an edge of \mathcal{H} .*

Proof of the claim. Assume $u \in V(G) \setminus (D_1 \cup D_2)$ is adjacent to some $v_1 \in D_1$ that forms an empty connected component of \mathcal{H} . Let $v_2 \in D_2$ be any neighbour of u . If v_1 is the only neighbour of u in D_1 , then note that, due to the edge uv_2 , by removing v_1 from D_1 and adding u to D_1 , we would end up with two new independent sets as D_1 and D_2 inducing one less empty connected component in \mathcal{H} , a contradiction to our choice of D_1 and D_2 . So, v_1 cannot be the only neighbour of u in D_1 . Let thus $v'_1 \in D_1$ be another neighbour of u . Now, since D_1 is independent, and v_1 is isolated in \mathcal{H} , the fact that G is claw-free implies that $v'_1 v_2$ must be an edge of \mathcal{H} . \diamond

As in the proof of Theorem 3.2, we also partition $V(G) \setminus (D_1 \cup D_2)$ into V_0 , V_1 , and V_2 forming a balanced tripartition of $G - D_1 - D_2$. We also reuse the notions of inner, upward, forward, and backward edges.

The distinguishing $(2, 2)$ -labelling of G we construct below will again be obtained through four main labelling steps, followed to produce a labelling which is very reminiscent to that we aimed at producing in the proof of Theorem 3.2. The structure of claw-free graphs is less permissive than that of $2K_2$ -free graphs however, so, in several occasions, our distinguishing and labelling rules will have to be tweaked by a bit.

In particular, the most troublesome point is the possible presence, in \mathcal{H} , of bad connected components. Note indeed that if $v_1 v_2$ is a bad connected component, then the fact that v_1 and v_2 are eventually distinguished does not rely at all on the choice of the label assigned to $v_1 v_2$. This means that, throughout the proof, whenever labelling an upward edge uv_i (with $u \in V_0 \cup V_1 \cup V_2$ and $i \in \{1, 2\}$), we have to wonder whether assigning a certain label to uv_i might result in v_1 and v_2 being impossible to distinguish later on. To guarantee v_1 and v_2 can be distinguished, we will, here, sometimes have to assign blue labels to upward edges. One problem, however, is that blue sums, in the proof of Theorem 3.2, were

the main way to guarantee that vertices in $D_1 \cup D_2$ can be distinguished from vertices in $V_0 \cup V_1 \cup V_2$. To counter this, we will need to guarantee that vertices in $V_0 \cup V_1 \cup V_2$ have “large” blue sums, while those in $D_1 \cup D_2$ have “small” blue sums.

With respect to these considerations, we introduce a bit more terminology for the bad connected components. Let $H = v_1v_2$ be a bad connected component of \mathcal{H} . At any time of our labelling steps below, we say that H is *tamed* if exactly one of v_1 and v_2 is incident to an edge assigned blue label 1, while it is *wild* otherwise. The point is that, once H gets tamed, then v_1 and v_2 will necessarily be distinguishable at any time as long as all of their other incident edges are assigned red labels. Now, if H is an untamed connected component of \mathcal{H} , then H is said *dangerous* if, omitting v_1v_2 , all edges incident to v_1 and v_2 that remain to be labelled are incident to the same vertex $u \in V_0 \cup V_1 \cup V_2$. Those conditions mean that all upward edges incident to v_1 and v_2 have been labelled, except for at most two of them, being incident to u . So, the task of making sure v_1 and v_2 are distinguished will need to be handled when labelling the upward edges incident to u .

Step 1: Labelling the inner, upward, and forward edges incident to V_0 .

In this step, we perform the following steps:

1. We start by assigning blue label 2 to all inner edges incident to vertices of V_0 .
2. We next consider every vertex $u \in V_0$ in turn, and assign a label to all its incident upward edges in the following way. Recall that, because G is claw-free, the upward edges incident to u go to at most two connected components of \mathcal{H} .
 - Assume all upward edges incident to u go to only one connected component $H \in \mathcal{H}$. Since u is incident to at least two upward edges, H cannot be empty.
 - Assume H is bad and wild. Then u is incident to exactly two upward edges uv_1 and uv_2 , where $H = v_1v_2$. Here, we assign red label 1 to uv_1 and blue label 1 to uv_2 , thereby taming H .
 - Assume H is nice or tamed. Let uv be any upward edge incident to H . We here assign red label 1 to uv , and red label 2 to all other upward edges incident to u .
 - Assume now all upward edges incident to u go to two connected components $H_1, H_2 \in \mathcal{H}$.
 - If, say, H_1 is empty, then, by Claim 4.3, it cannot be that H_2 is also empty. Denote by v the unique vertex of H_1 . If H_2 is nice or tamed, then we assign red label 1 to uv and red label 2 to all upward edges incident to u going to H_2 . Otherwise, H_2 is wild, in which case we assign red label 1 to uv , blue label 1 to any one upward edge incident to u going to H_2 (taming H_2), and red label 2 to the other upward edge to H_2 (which exists by Claim 4.3).
 - If H_1 and H_2 are both nice or tamed, then we assign red label 1 to any one upward edge incident to u going to H_1 or H_2 , and red label 2 to all others.
 - If H_1 is wild and H_2 is nice or tamed, then we assign blue label 1 to any upward edge incident to u going to H_1 (thereby taming H_1), red label 1 to any upward edge going to H_2 , and red label 2 to all other upward edges.
 - If H_1 and H_2 are both wild, then we claim they cannot be both dangerous. Indeed, let $x \in V_1$ be any neighbour of u . Since G is claw-free, note that a neighbour of u in H_1 , one in H_2 , and x must be joined by an edge, which

would contradict the fact that H_1 and H_2 are bad and dangerous. Thus, we may assume, w.l.o.g., that H_1 is not dangerous. Then we assign red label 1 to an upward edge incident to u going to H_1 , blue label 1 to any upward edge going to H_2 (taming H_2), and red label 2 to all other upward edges.

As a result, note that, after any of the cases above, $\sigma_r(u)$ is necessarily odd. Also, the only situations where a wild connected component adjacent to u was not tamed, are when that connected component is not dangerous, because it is adjacent to a vertex in V_1 . For every tamed connected component of \mathcal{H} , note that only one of its two vertices is incident to an upward edge assigned a blue label, with value 1.

3. Last, let u_1, \dots, u_n be an ordering over the vertices of V_0 in increasing order over their degrees (in V_0), and consider the u_i 's one by one in order. For every u_i considered that way, denote by u_{i_1}, \dots, u_{i_d} the $d \geq 0$ neighbours of u_i in V_0 that precede u_i in the ordering. If $d = 0$, then assign blue label 2 to all edges incident to u_i going to V_1 . Now, if $d \geq 1$, then recall that u_i is incident to $d_{V_1}(u_i) \geq d$ edges going to V_1 . By assign red label 2 to none, one, two, etc., or all of these edges, and blue label 2 to all others, we can increase the red sum of u_i by any amount in $\{0, 2, \dots, 2d_{V_1}(u_i)\}$, which is a set of at least $d + 1$ elements. There is thus a way to assign red label 2 to at most d edges incident to u_i going to V_1 , and blue label 2 to the rest, so that the red sum of u_i is different from the red sums of u_{i_1}, \dots, u_{i_d} .

Once the labelling process above is achieved, note that all vertices of V_0 have their red sum being odd, while every two adjacent vertices of V_0 are distinguished by their red sums. Also, every vertex of V_0 has blue sum at least 2, due either to an incident inner edge, or to an incident forward edge. The only edges incident to the vertices of V_0 that are not labelled yet are backward edges, which will be assigned blue labels during a later step. Also, all forward edges incident to the vertices in V_0 were labelled, assigned red label 2 or blue label 2. Finally, recall that we tamed the bad connected components of \mathcal{H} whenever possible (as described above).

In later Step 3, the forward edges incident to the vertices in V_2 (thus going to V_0) will all be assigned blue labels. Thus, already at this point, we can predict that, in most cases, actually the vertices of V_0 will have blue sum at least 3. There are a few peculiar cases, however, where this could not be the case, which might cause eventual problems. For this reason, we need, right away, to possibly modify the current labelling a bit, to guarantee the vertices of V_0 will eventually either have odd red sum and blue sum at least 3, or verify other colour conditions.

Since we have assigned blue label 2 to all inner edges incident to the vertices in V_0 , any vertex of V_0 has blue sum at least 4 provided it is incident to at least two inner edges. Likewise, since, in Step 3, all backward edges incident to the vertices of V_0 will be assigned blue labels, any vertex of V_0 will have blue sum at least 3 provided it is incident to at least one inner edge and at least one backward edge. Furthermore:

- If a vertex $u \in V_0$ is incident to no inner edge (so, $d_{V_0}(u) = 0$), then, since we assigned blue label 2 to all forward edges incident to u , eventually we will have $\sigma_b(u) \geq 3$ as soon as u is incident to at least two forward edges, or to only one forward edge and at least one backward edge. Similarly, we will have $\sigma_b(u) \geq 3$ if we assigned a blue label to any upward edge incident to u .
- Consider now the case of a vertex $u \in V_0$ incident to a single inner edge (so, $d_{V_0}(u) = 1$). Again, eventually $\sigma_b(u)$ will be achieved, provided u is incident to at least

one backward edge. Recall also that, in the third step above (when we labelled all forward edges), we considered the vertices with the lowest degrees first, and, through the procedure, we did our best to assign blue label 2 to the forward edges as much as possible. In particular, the only reason why we were perhaps not able to assign blue label 2 to any of the forward edges incident to u , is because u is incident to only one forward edge, and the only neighbour $u' \in V_0$ of u in V_0 was treated earlier in the process, and thus also verifies $d_{V_0}(u') = 1$. In that case, however, a forward edge incident to u' must have been assigned blue label 2, and thus eventually we will have $\sigma_b(u') \geq 4$.

So, the vertices u of V_0 for which we might end up with $\sigma_b(u) = 2$ are those with:

- $d_{V_2}(u) = d_{V_0}(u) = 0$ and $d_{V_1}(u) = 1$.
- $d_{V_2}(u) = 0$ and $d_{V_0}(u) = d_{V_1}(u) = 1$, and the unique neighbour u' of u in V_0 verifies $d_{V_0}(u') = 1$ and $\sigma_b(u') \geq 4$.

We now perform label modifications around any such u . So, u is incident to no backward edge, to exactly one forward edge, and to at most one inner edge (which is assigned blue label 2). We unlabel all upward and forward edges incident to u . Then, the red sum of u becomes precisely 0. We relabel all these edges in the following way:

- Assume the upward edges incident to u go to only one connected component H of \mathcal{H} . Then, H is not empty. If H is nice or tamed, then we assign red label 2 to all but at most two upward edges incident to u , assign red label 1 or red label 2 to the remaining two edges so that the red sum of u becomes congruent to 2 modulo 4, and finally assign blue label 2 to the only forward edge incident to u . Now, if H is wild, then we assign blue label 1 to any upward edge incident to u (so that we tame H), red label 2 to the second upward edge going to H , and blue label 2 to the forward edge incident to u .
- Now assume the upward edges go to two connected components $H_1, H_2 \in \mathcal{H}$.
 - If H_1 is empty, then H_2 is not empty, and u is incident to at least two upward edges going to H_2 . If H_2 is wild, then we start by assigning blue label 1 to any upward edge incident to u going to H_2 (so that H_2 is tamed). There now remain at least two upward edges to be labelled. By assigning red labels to them, we can make sure the red sum of u becomes congruent to 2 modulo 4. Eventually, we assign blue label 2 to the forward edge incident to u . Now, if H_2 is nice, then we assign red labels to the at least three upward edges incident to u so that its red sum, again, becomes congruent to 2 modulo 4, before assigning blue label 2 to the forward edge incident to u .
 - If H_1 and H_2 are both nice, then we assign red labels to the upward edges incident to u so that its red sum becomes congruent to 2 modulo 4, before assigning blue label 2 to its incident forward edge.
 - If, say, H_1 is wild while H_2 is nice or tamed, then we assign blue label 1 to any upward edge going to H_1 , so that H_1 is tamed. There now remains at least one upward edge to be labelled. Since, currently, the red sum of u is 0, we can assign red labels to these edges so that the red sum of u becomes congruent to 2 modulo 4. Lastly, we assign blue label 2 to the forward edge incident to u .

- If H_1 and H_2 are both wild, then, because u has a neighbour in V_1 , it cannot be, since G is claw-free, that they are actually dangerous. Assume w.l.o.g. that H_1 is not dangerous. We assign blue label 1 to any upward edge incident to u going to H_2 , thereby taming H_2 . Now, we assign red labels to the other upward edges so that the red sum of u becomes congruent to 2 modulo 4. Then, we assign blue label 2 to the forward edge incident to u .

In all cases, note that we end up with $\sigma_r(u) \equiv 2 \pmod{4}$ and $\sigma_b(u) \geq 2$. Meanwhile, the other vertices of V_0 , to which the extra care above was not applied, still have odd red sum and blue sum at least 3. Furthermore, we still have that all edges joining vertices of V_0 and V_1 are assigned red label 2 or blue label 2.

Step 2: Labelling the inner, upward, and forward edges incident to V_1 .

We now deal with the vertices in V_1 , which we do as follows. Consider every connected component C of $G[V_1]$ in turn. Let r be a vertex of maximum degree in C , *i.e.*, with $d_C(r)$ as large as possible. Now let T be any spanning tree of C having r as its root. This defines a natural orientation of T , from which we can infer notions of vertices being more or less deep in T , w.r.t. r . In particular, any edge $uu' \in T$, assuming u is closer to r than u' is, is a *parent edge* incident to u' , and a *child edge* incident to u . Note that r is incident to no parent edge, the leaves of T are incident to no child edges, while every other vertex is incident to exactly one parent edge and at least one child edge.

We now label edges incident to the vertices in C as follows:

1. We start by assigning blue label 2 to all edges of $E(C) \setminus E(T)$.
2. We now consider the vertices of C one by one, considering them according to their decreasing distance to r in T . Whenever considering a vertex u this way, we will label its incident parent edge (if it exists) and its incident upward edges. This way, note that, whenever considering a new $u \in V(C)$, all its child edges can be assumed to be labelled. Also, through what follows we will always assign a blue label or red label 2 to any incident parent edge. Since all edges joining vertices in V_0 and V_1 have been assigned blue labels and red label 2, this implies that, when starting considering a new $u \in V(C)$, currently its red sum can be assumed to be even.

We consider two main cases, treating r in a particular way. Note that it is possible that C consists of r only, and thus that r is a root with no neighbours.

- Assume we are currently considering a non-root vertex $u \in V(C)$. As mentioned earlier, the only edge of C incident to u that remains to be labelled is the parent edge uu' . Also, currently, $\sigma_r(u) \equiv 0 \pmod{2}$. Since G is claw-free, recall that the upward edges incident to u go to at most two connected components of \mathcal{H} .
 - Assume first all upward edges incident to u go to a single connected component H of \mathcal{H} . Then H cannot be empty, since u is incident to at least two upward edges.
 - * If H is bad and wild, then $H = v_1v_2$ with uv_1 and uv_2 being the exact two upward edges incident to u . If $\sigma_r(u) \equiv 0 \pmod{4}$, then we assign red 2 to uv_1 and uu' , and blue label 1 to uv_2 (thereby taming H). Otherwise, *i.e.*, if $\sigma_r(u) \equiv 2 \pmod{4}$, then we assign blue label 1 to uv_1 (taming H), red label 2 to uv_2 , and blue label 2 to uu' .

- * Otherwise, H is nice or tamed. Here, we assign red label 2 to all upward edges incident to u but at most two of them, to which we both assign either red label 1 or red label 2, so that the red sum of u becomes a multiple of 4. We then assign blue label 2 to uu' .
- Now assume the upward edges incident to u go to two connected components $H_1, H_2 \in \mathcal{H}$.
 - * Again, if, say, H_1 is empty, then H_2 cannot be empty by Claim 4.3. If H_2 is nice or tamed, then we assign red label 2 to all upward edges incident to u but at most two of them, to which we both assign either red label 1 or red label 2 so that the red sum of u becomes a multiple of 4, before assigning blue label 2 to uu' . Otherwise, if H_2 is wild, then we assign blue label 1 to any upward edges incident to u going to H_2 , so that H_2 is tamed. Now, recall that, by Claim 4.3, there must remain at least two upward edges incident to u to be labelled, and thus we can proceed as previously to reach the same conclusions.
 - * If H_1 and H_2 are both nice or tamed, then we assign red label 2 to all upward edges incident to u but at most two of them, to which we both assign either red label 1 or red label 2 so that the red sum of u becomes a multiple of 4. We then assign blue label 2 to uu' .
 - * If, say, H_1 is wild while H_2 is nice or tamed, then we assign blue label 1 to any upward edge incident to u going to H_1 (so that H_1 is currently tamed). If there remain at least two upward edges incident to u to be labelled, then, as previously, we assign red label 1 or 2 to these edges so that the red sum of u becomes a multiple of 4, before assigning blue label 2 to uu' . Otherwise, only one upward edge uv (with $v \in V(H_2)$) remains to be labelled, which means that H_1 is actually dangerous, and that there is only one upward edge uv' incident to u going to H_1 . If, currently, we have $\sigma_r(u) \equiv 2 \pmod{4}$, then we assign red label 2 to uv , and blue label 2 to uu' . Otherwise, $\sigma_r(u) \equiv 0 \pmod{4}$. If changing to red label 2 the label assigned to uv' does not create any conflict between the two vertices of H_1 , then we also assign red label 2 to uv , and blue label 2 to uu' . Otherwise, if changing to red label 2 the label assigned to uv' creates a conflict between the two vertices of H_1 , then we assign red label 1 to uv' and uv , and red label 2 to uu' .
 - * If H_1 and H_2 are both wild, then, just as in the previous case, due to the existence of a forward edge incident to u , we deduce that at least one of H_1 and H_2 must be not dangerous. Assume w.l.o.g. that H_1 is not dangerous. We start by assigning blue label 1 to any upward edge incident to u going to H_2 , so that H_2 is tamed. Again, if there remain at least two upward edges incident to u to be labelled, then, by assigning red labels to these edges, we can make sure the red sum of u becomes a multiple of 4, before eventually assigning blue label 2 to uu' . Otherwise, u is incident to exactly two upward edges uv and uv' , with $v \in V(H_1)$ and $v' \in V(H_2)$ and thus H_2 is dangerous). Depending on whether $\sigma_r(u) \equiv 0 \pmod{4}$ or $\sigma_r(u) \equiv 2 \pmod{4}$, just as in the previous case, we can, if needed, change the label assigned to uv' , before labelling uv and uu' , so that the red sum of u becomes a multiple of 4, there is no conflict between the vertices of H_2 , and uu' is assigned either blue label 2 or red label 2.

In all cases above, note that we, after treating u , we get $\sigma_r(u) \equiv 0 \pmod{4}$, and also $\sigma_b(u) \geq 1$. Also, the parent edge incident to u is always assigned blue label 2 or red label 2. Finally, the only situation where we did not tame a bad component adjacent to u , is when that bad component was not dangerous yet (because it is adjacent to a vertex in V_2), or because it was dangerous but we managed to assign a red label to an incident upward edge without creating any conflict between its two vertices.

- Now consider the case where $u = r$. Due to the order in which we considered the vertices of C , we have that all edges incident to u in C are currently labelled, with blue label 2 or red label 2, which is also the case for the edges joining vertices of V_0 and V_1 . So, $\sigma_r(u)$ is currently even.

So, we focus on labelling the upward edges incident to u . Recall that they go to at most two connected components of \mathcal{H} . Note that, below, we mark with some “★” symbols two technical places of the proof for which extra explanations are needed. These places are discussed right after the case distinction.

- Assume first all upward edges incident to u go to exactly one connected component H of \mathcal{H} . Then, H cannot be empty by Claim 4.3.
 - * If H is bad and wild, then $H = v_1v_2$ and uv_1 and uv_2 are the exact two upward edges incident to u . If H is not dangerous, then we assign red label 1 or red label 2 to both uv_1 and uv_2 , so that the red sum of u becomes a multiple of 4. Now assume H is dangerous. If $\sigma_r(u) \equiv 2 \pmod{4}$, then we assign blue label 1 to uv_1 (thereby taming H) and red label 2 to uv_2 . Now, if $\sigma_r(u) \equiv 0 \pmod{4}$, then we assign blue label 1 to uv_1 and blue label 2 to uv_2 .★
 - * Otherwise, H is tamed or nice. Here, we assign red label 2 to all but at most two upward edges incident to u , to both of which we either assign red label 1, or assign red label 2, so that the red sum of u becomes a multiple of 4.
- Assume second that the upward edges incident to u go to two connected components $H_1, H_2 \in \mathcal{H}$.
 - * If H_1 is empty, then, by Claim 4.3, H_2 cannot be empty and u is incident to at least two upward edges going to H_2 . If H_2 is nice or tamed, then we first assign red label 2 to all but at most two upward edges incident to u . To the remaining two upward edges, we then either assign red label 1, or assign red label 2, so that the red sum of u becomes a multiple of 4. Now, consider the case where H_2 is wild. Here, we assign blue label 1 to an upward edge going to H_2 (so that H_2 is tamed), before assigning red labels to the remaining ones so that the red sum of u becomes a multiple of 4. This is indeed possible, since there are two such edges.
 - * If H_1 and H_2 are both nice or tamed, then we assign red label 2 to all upward edges incident to u but at most two of them, to which both we assign red label 1 or red label 2 so that $\sigma_r(u)$ becomes a multiple of 4.
 - * Assume here that, say, H_1 is wild and H_2 is nice or tamed. If u is incident to at least three upward edges, then we assign blue label 1 to any edge going to H_1 (thereby taming H_1), before assigning red labels to the remaining upward edges so that the red sum of u becomes a multiple of 4. Now, assume u is incident to only one upward edge uv_1 going to H_1 , and only one upward edge uv_2 going to H_2 . If $\sigma_r(u) \equiv 2 \pmod{4}$,

then we assign blue label 1 to uv_1 (so that H_1 is tamed) and red label 2 to uv_2 . Lastly, suppose $\sigma_r(u) \equiv 0 \pmod{4}$. If we cannot assign red label 2 to uv_1 (which would allow us to also assign red label 2 to uv_2), then it means that H_1 is dangerous. Regarding v_2 , since G is claw-free and H_2 is thus a path or a cycle, it must be that $d_{H_2}(v_2) = 1$ (as otherwise u would be adjacent to another vertex of H_2 , and there would be at least three upward edges incident to u , a case we handled earlier). In this case, we assign blue label 1 to both uv_1 (taming H_1) and uv_2 .★★

- * If H_1 and H_2 are both wild, then, again, because G is claw-free and u has at least one neighbour in V_2 , we deduce that H_1 and H_2 cannot both be dangerous. Assume H_1 is not dangerous. We start by assigning blue label 1 to an upward edge uv' incident to u going to H_2 , so that H_2 is tamed. If there remain at least two upward edges to be labelled, then, once more, by assigning red labels to these edges we can make sure the red sum of u becomes a multiple of 4. Otherwise, there remains only one such edge uv , going to H_1 . If $\sigma_r(u) \equiv 2 \pmod{4}$, then we assign red label 2 to uv . Otherwise, we have $\sigma_r(u) \equiv 0 \pmod{4}$, in which case we assign blue label 1 to uv , thereby taming H_1 .

In all these cases, we, again, always end up with $\sigma_r(u) \equiv 0 \pmod{4}$. Note that, this time, there are cases where we end up with $\sigma_b(u) = 0$. We also need to discuss technical points related to the places we marked with stars.

- ★ This place of the proof is the only one where we label an upward edge with blue label 2. This upward edge assigned label 2 goes to a wild connected component $H = v_1v_2$ of \mathcal{H} that is dangerous. This means that, later on in the process, no further upward edge going to H can be considered, and thus that the blue sums of v_1 and v_2 , provided we eventually assign a red label to v_1v_2 , will remain 1 and 2 (thus distinguishing these two vertices).
- ★★ This place of the proof is the only one where an upward edge uv going to a nice or tamed connected component H is assigned a blue label (with value 1). Recall that we must have $d_H(v) = 1$.
 - If H is nice, then note that this place of the proof is actually the only one where an upward edge incident to v can be assigned a blue label, with value 1. More precisely, an upward edge uv is assigned blue label 1 only if u is the root we have chosen for some connected component of $G[V_1]$, and v is the only neighbour of u in H . This means that v cannot be incident to two such edges, as otherwise there would be two vertices u and u' belonging to distinct connected components of $G[V_1]$ sharing v as a common neighbour, which is not possible as, because G is claw-free, we would deduce either that u and u' are adjacent (thereby being part of a single connected component of $G[V_1]$), or that one of u and u' is also adjacent to the unique neighbour of v in H . This means that v , throughout Step 2, must remain of blue sum at most 1.
 - If H is tamed, then a technical point is that v might be incident to the edge assigned a blue label that permitted to tame H in the first place. In particular, note that it is possible that H was tamed during Step 1. In such a case, by the same arguments as above, we deduce that, during Step 2, at most one root vertex can be incident to an upward edge going to v to which

we assigned blue label 1. This means that, all along Step 2, v must remain of blue sum at most 2.

3. Last, we consider the vertices of C one by one, following any ordering u_1, \dots, u_n where $u_1 = r$ (that is, we consider r first). For every u_i considered that way, let u_{i_1}, \dots, u_{i_d} denote the $d \geq 0$ neighbours of u_i in C that have already been treated. If $d = 0$, then we assign label 2 to all forward edges (going to V_2) incident to u_i . Otherwise, u_i is incident to $d_{V_2}(u_i) \geq d$ forward edges, and by assigning blue labels to these edges we can increase the blue sum of u_i by any amount in $\{d_{V_2}(u_i), \dots, 2d_{V_2}(u_i)\}$, a set of $d_{V_2}(u_i) + 1 \geq d + 1$ values. So we can assign blue labels to the forward edges incident to u_i so that its eventual blue sum is different from those of u_{i_1}, \dots, u_{i_d} . We do this so that the blue sum of u_i is always as large as possible.

Once every vertex u of V_1 has been treated that way, note that it must verify $\sigma_r(u) \equiv 0 \pmod{4}$. We claim it must also verify $\sigma_b(u) \geq 2$. Indeed, if $d_{V_1}(u) = 0$, then all forward edges of u are assigned blue label 2, and the claim holds. Otherwise, if $d_{V_1}(u) \geq 1$, then either u is not the root of C , in which case, as mentioned earlier, at least one upward edge or inner edge incident to u is assigned a blue label, which, together with an incident forward edge, yields $\sigma_b(u) \geq 2$; or u is the root of C , in which case we treated r first in the third step above, which means, since we maximised the resulting blue sums, that all its incident forward edges are assigned blue label 2, yielding $\sigma_b(u) \geq 2$.

Note also that all edges joining vertices of V_1 and V_2 have been assigned blue labels. Also, as pointed out earlier, the only vertices v of \mathcal{H} that currently have non-zero blue sum verify $\sigma_b(v) \leq 2$. Also, denoting $H \in \mathcal{H}$, we have $d_H(v) = 1$.

Step 3: Labelling the inner, upward, and forward edges incident to V_2 .

Now, we deal with the vertices of V_2 . Recall that only the backward edges incident to these vertices have been labelled at this point, and they were assigned blue labels. We label their remaining incident edges in the following way.

1. We first assign blue label 2 to all inner edges incident to the vertices of V_2 .
2. Next, we consider every vertex $u \in V_2$ in turn, and label its incident upward edges. Again, since G is claw-free, the upward edges incident to u go to at most two connected components of \mathcal{H} . Also, currently $\sigma_r(u) = 0$.
 - Assume first all upward edges incident to u go to a single connected component H of \mathcal{H} . Again, H cannot be empty.
 - If H is bad and wild, then u is incident to exactly two upward edges uv_1 and uv_2 with $H = v_1v_2$. In this case, we assign blue label 1 to uv_1 and red label 2 to uv_2 , so that we get $\sigma_r(u) \equiv 2 \pmod{4}$, and we tame H .
 - Otherwise, *i.e.*, H is nice or tamed, then we assign red label 2 to all upward edges incident to u but at most two of them, to both of which we assign either red label 1 or red label 2 so that we get $\sigma_r(u) \equiv 2 \pmod{4}$.
 - Second, assume all upward edges incident to u go to two connected components $H_1, H_2 \in \mathcal{H}$.
 - If H_1 is empty, then, by Claim 4.3, H_2 is not empty, and u is incident to at least two upward edges going to H_2 . If H_2 is wild, then we assign blue label 1 to any upward edge incident to u going to H_2 , so that H_2 is tamed;

there then remain at least two upward edges to be labelled, to which we assign red labels so that we get $\sigma_r(u) \equiv 2 \pmod{4}$. Otherwise, H_2 is nice and tamed, in which case we assign red label 2 to all but at most two upward edges incident to u , to both of which we either assign red label 1 or red label 2 so that we get $\sigma_r(u) \equiv 2 \pmod{4}$.

- If H_1 and H_2 are both nice or tamed, then we assign red label 2 to all but at most two upward edges incident to u , to both of which we assign either red label 1 or red label 2 so that we obtain $\sigma_r(u) \equiv 2 \pmod{4}$.
- If H_1 is wild and H_2 is nice or tamed, then we first assign blue label 1 to any upward edge incident to u going to H_1 (thereby taming H_1). There then remain at least one upward edge to be labelled. If there is only one such edge, then we assign red label 2 to it. Otherwise, we assign red label 2 to all but at most two remaining upward edges incident to u , to both of which we either assign red label 1 or red label 2. In all cases, we obtain $\sigma_r(u) \equiv 2 \pmod{4}$.
- Now assume both H_1 and H_2 are wild, and let v be any vertex of H_1 adjacent to u , and v' be any vertex of H_2 adjacent to u . We start by assigning blue label 1 to both uv and uv' , thereby taming H_1 and H_2 . If there remain at least one upward edge incident to u to be labelled, then we assign red labels to those edges so that we get $\sigma_r(u) \equiv 2 \pmod{4}$. Otherwise, it means that uv and uv' are the only two upward edges incident to u , and thus that H_1 and H_2 are both dangerous. In that case, let us relabel both uv and uv' with red label 1. If this raises no conflicts, then we leave things as is, and we get $\sigma_r(u) \equiv 2 \pmod{4}$. Otherwise, if both v and v' get in conflict with their unique neighbour in H_1 and H_2 , respectively, then we relabel uv with blue label 1 and uv' with red label 2. This way, note that $\sigma_r(u) \equiv 2 \pmod{4}$, while v and v' are not involved in conflicts. Last, if, when having uv and uv' being assigned red label 1, only, say, v is in conflict with its neighbour in H_1 , then we relabel uv with red label 2 and uv' with blue label 1. We then reach the same conclusions as in the previous case.

After performing this labelling step, we get $\sigma_r(u) \equiv 2 \pmod{4}$ in all cases. All bad connected components adjacent to u have been either tamed, or their incident edges have been labelled so that its two adjacent vertices cannot be in conflict. Also, when taming a wild connected component, we did so by assigning blue label 1 to an incident edge.

3. Now, as previously, let u_1, \dots, u_n be an arbitrary ordering over the vertices of V_2 , and consider the u_i 's one by one in any order. For every u_i considered like this, let u_{i_1}, \dots, u_{i_d} be the $d \geq 0$ neighbours of u_i in V_2 preceding u_i in the ordering. If $d = 0$, then assign blue label 2 to all forward edges incident to u_i , going to V_0 . Now, if $d \geq 1$, then recall that u_i is incident to $d_{V_0}(u_i) \geq d$ forward edges. By assigning blue labels to these edges, we can thus make the blue sum of u_i increase by any amount in $\{d_{V_0}(u_i), \dots, 2d_{V_0}(u_i)\}$, thus in $d_{V_0}(u_i) + 1 \geq d + 1$ possible ways. So we can assign blue labels to the forward edges incident to u_i so that the blue sum of u_i is different from the blue sums of u_{i_1}, \dots, u_{i_d} .

At this point of the proof, note that all edges incident to the vertices in V_0 , V_1 , and V_2 have been labelled. For all vertices $u \in V_0$, we either have $\sigma_r(u) \equiv 1 \pmod{2}$ and $\sigma_b(u) \geq 3$, or $\sigma_r(u) \equiv 2 \pmod{4}$, $\sigma_b(u) \geq 2$, and u is not adjacent to any vertex in V_2 and has no

neighbour in V_0 having its red sum verifying the same property. For all vertices $u \in V_1$, we have $\sigma_r(u) \equiv 0 \pmod{4}$ and $\sigma_b(u) \geq 2$. For all vertices $u \in V_2$, we have $\sigma_r(u) \equiv 2 \pmod{4}$ and $\sigma_b(u) \geq 2$. Furthermore, forward edges were labelled so that adjacent vertices with odd red sum in V_0 are distinguished w.r.t. their red sums, adjacent vertices in V_1 are distinguished w.r.t. their blue sums, and similarly for adjacent vertices in V_2 . So, any two adjacent vertices in $V_0 \cup V_1 \cup V_2$ are distinguished by the current partial labelling.

Now, regarding any connected component $H \in \mathcal{H}$, in general its vertices should have blue sum zero. Precisely, the only vertices $v \in V(H)$ with $\sigma_b(v) > 0$ verify $\sigma_b(v) \leq 2$. Those with $\sigma_b(v) = 2$ verify $d_H(v) = 1$. The typical cases in which this occurs, is when H is bad, in which case its only two vertices have blue sum 1 and 2. Otherwise, if $\sigma_b(v) = 1$, then most of the times H is bad, in which case only one blue edge incident to the two vertices of H is assigned blue label 1 (in order to tame H). It is also possible to have $\sigma_b(v) = 1$ when H is a path of length at least 2, in which cases v must be an end of that path.

Step 4: Labelling the edges of \mathcal{H} .

We now consider the edges of every connected component $H \in \mathcal{H}$. Recall that H can be of three main types, which we treat as follows:

- If H is bad, then H has only one edge v_1v_2 . By how we labelled the upward edges through Steps 1 to 3, recall that v_1v_2 are already distinguished, by either their red sums or by their blue sums. In particular, if we do not have $\sigma_b(v_1) = \sigma_b(v_2) = 0$, then v_1 and v_2 cannot have the same blue sum. Also, we have $\sigma_b(v_1), \sigma_b(v_2) \leq 2$, while, in V_0 , all vertices u with $\sigma_r(u) \equiv 1 \pmod{2}$ verify $\sigma_b(u) \geq 3$. Also, all other vertices u in $V_0 \cup V_1 \cup V_2$ verify $\sigma_b(u) \geq 2$.

By all these arguments, it can be noted that, by assigning a red label to v_1v_2 so that, assuming $\sigma_b(v_1) \geq \sigma_b(v_2)$, we get $\sigma_r(v_1) \equiv 1 \pmod{2}$, then we cannot get any conflict involving a vertex of H and one of $V_0 \cup V_1 \cup V_2$.

- If H is a path $p_1 \dots p_k$ of length $k - 1$ at least 2, then recall that $\sigma_b(p_1), \sigma_b(p_k) \leq 1$ while $\sigma_b(p_2) = \sigma_b(p_{k-1}) = 0$, while $\sigma_b(u) \geq 2$ for every $u \in V_0 \cup V_1 \cup V_2$. So, upon assigning only red labels to the edges of H , we cannot get a conflict between vertices of H and vertices in $V_0 \cup V_1 \cup V_2$. Now, by Lemma 2.3 or 2.4, we can assign red labels to the edges of H so that its adjacent vertices, when taking into account how we labelled the upward edges, are distinguished by their red sums.
- If H is a cycle $v_1 \dots v_kv_1$ of even length, then recall that $\sigma_b(v_i) = 0$ for every $i \in \{1, \dots, k\}$, while, again, $\sigma_b(u) \geq 2$ for every $u \in V_0 \cup V_1 \cup V_2$. So, provided we assign blue label 1 to edges forming a matching of H and red labels to the red, we cannot get conflicts involving vertices of H and vertices of $V_0 \cup V_1 \cup V_2$. Here, Lemma 2.5 tells us we can label the edges of H this way, so that any two of its adjacent vertices are distinguished.

By all these arguments, we end up with a distinguishing $(2, 2)$ -labelling of G . □

5. Conclusion

In this work, we proved the Weak $(2, 2)$ -Conjecture for $2K_2$ -free graphs and $K_{1,3}$ -free graphs, two classes of graphs for which the 1-2-3 Conjecture is not known to hold. Another source of interest for those graphs is that they have unbounded chromatic number.

Proving the Weak $(2, 2)$ -Conjecture in full, or even the 1-2-3 Conjecture itself, would of course be the main achievement that one could hope for in this field. Towards this, one could also, for similar reasons as the ones which motivated us, first focus on proving the Weak $(2, 2)$ -Conjecture for more classes of graphs, such as other graph classes defined in terms of forbidden induced structures. As such, we believe it could be interesting to wonder about triangle-free graphs, or only graphs with large girth in general. Conversely, one could wonder about graphs in which many short cycles are present, such as chordal graphs. Another class of graphs could be e.g. that of P_4 -free graphs (a.k.a. cographs).

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