Bounds for Point Recolouring in Geometric Graphs

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Abstract

We examine a recolouring scheme ostensibly used to assist in classifying geographic data. Given a drawing of a graph with bi-chromatic points, where the points are the vertices of the graph, a point can be recoloured if it is surrounded by neighbours of the opposite colour. The notion of surrounded is defined as a contiguous subset of neighbours that span an angle greater than 180 degrees. The recolouring of surrounded points continues in sequence, in no particular order, until no point remains surrounded. We show that for some classes of graphs the process terminates in a polynomial number of steps. On the other hand, there are classes of graphs with infinite recolouring sequences.

Key words: computational geometry, point recolouring, triangulation, geometric graph

1. Introduction

Given a set of planar points partitioned into red and blue subsets, a red-blue separator is a boundary that separates the red points from the blue ones. There has been considerable investigation of methods for obtaining such red-blue separating boundaries.

In his PhD thesis, Seara [12], examines various means for red-blue separation, including all feasible red-blue separations by a line, by a strip, or by a wedge. For the case of red-blue separation with the minimum perimeter polygon the problem is known to be NP-hard [3, 1]. A somewhat related topic is to obtain a balanced subdivision of red and blue points, that is, faces of the subdivision contain a prescribed ratio of red and blue points. Kaneko and Kano [4] give a comprehensive survey of results pertaining to red and blue points in the plane, including results on balanced subdivisions.

For some applications one is willing to reclassify points by recolouring them so as to obtain a more reasonable boundary. For example, Chan [2] shows that finding a red-blue separating line with the minimum number of reclassified points takes $O((n + k^2) \log k)$ expected time, where k is the number of recoloured points.

Reinbacher et al. [11] study algorithms for delineating regions which are determined by coloured points. They propose a recolouring, or reclassification, method for obtaining better delineating boundaries. As a first step of the heuristic algorithm a triangulation of the points is used to specify a neighbour relation for the points. They then define a point, p, as *surrounded* when there is a contiguous set of oppositely coloured neighbours of p, in the triangulation, that span a radial angle greater than 180°. Points that are surrounded are recoloured iteratively in no particular order until no point remains surrounded. Using properties of the triangulation Reinbacher et al. show that these recolouring sequences are finite and are guaranteed to terminate in at most $2^n - 1$ iterations. Furthermore, Reinbacher et al. demonstrate, through experimental results, that this process does a good job of reclassifying points yielding boundaries that are more suitable for their application.

Recolouring problems have also been studied in other areas, in some cases under different names. For example, a recolouring-like problem applied to distributed systems with fault propagation has been examined by de la Noval

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et al. [6]. In their work, recolourings occur synchronously (in parallel). Peleg and others have studied recolourings in parallel, looking for initial configurations that make all the points converge to a single colour [10]. In his survey, Peleg poses some open problems regarding the study of asynchronous or sequential recolourings. His asynchronous model coincides with the iterative recolouring model discussed in this note; although for most of our results, except for Theorem 5, we rely on the geometry of the input graph rather than purely combinatorial features, such as the degree of the points. Also, we study the length of recolouring sequences instead of initial configurations that converge to a monochromatic configuration.

Our results begin where Reinbacher et al. leave off. Using some of their ideas we are able to obtain an $O(n^2)$ upper bound for the number of recolourings of a triangulated set of points. We also provide bounds for recolouring sequences in other types of geometric graphs (see Table 1 for a summary of our results on different types of geometric graphs). Preliminary versions of this work have appeared in [7, 8].

Table 1: Summary of main results. The column "All recoloured" indicates whether there is a recolouring sequence that recolours all points.

Type of graph	**Lower bound**	**Upper bound**	**All recoloured**	**Section**
Triangulations	$O(n^2)$	$O(n^2)$	No	3
Convex drawings	$O(n^2)$	$O(n^2)$	No	4.1
Max. degree three	$O(n)$	$O(n)$	No	4
Trees	$O(n)$	$O(n)$	No	4.3
Planar	∞	–	Unknown	4.1
Planar with adjacent convex vertices	$O(n^2)$	$O(n^2)$	No	4.1
Non-planar	∞	–	Yes	4.2
Non-planar containing convex drawing	$O(n^2)$	$O(n^3)$	No	4.2
One-bend planar	∞	–	Yes	5.1

In the next section we formally describe the recolouring problem and present some basic results. We also present some preliminary results obtained by Reinbacher et al. for their exponential upper bound proof. Section 3 precisely describes the recolouring problem in triangulations, including the lower bound by Reinbacher et al. and the new (tight) $O(n^2)$ upper bound. In Section 4 bounds are given for other types of straight-line drawings of graphs, such as planar graphs, non-planar graphs, and trees. The last section discusses some extensions of our results.

2. Preliminaries

The input of our recolouring problem consists of a bi-chromatic (red and blue) set of points S in the plane and a set of straight-line segments connecting pairs of points of S. Thus, the input defines a graph G, or more specifically, a drawing of G in the plane. We use the term graph drawing, or simply *drawing*, to refer to such straight-line drawing of a graph in the plane. Consider a drawing D of G in the following. We assume throughout, for simplicity of exposition, that the points of D are in general position and no two points share the same x-coordinate. We colour the edges of D red if its two incident points are red, and blue if its two incident points are blue. If one of the incident points is red and the other is blue we mix the colours to obtain a magenta edge.

The following definitions and lemmas follow, with a few minor modifications, the paper of Reinbacher et al. [11].

Definition1. Let the edges of a bi-chromatic straight-line drawing D be coloured as above. Then the **magenta angle** of a point $p \in S$ is:

- $0°$, if p has at most one radially consecutive incident magenta edge,
- $360°$, if p has degree greater than one and is incident only to magenta edges,
- the maximum angle between two or more radially consecutive incident magenta edges, otherwise.

Notice that, according to the previous definition, a point with only one neighbour in D has magenta angle $0°$ regardless of the colour of its neighbour (see Figure 1). A *surrounded* point is one with magenta angle greater than $180°$. Therefore, a point of degree 0 or 1 is never surrounded nor recoloured.

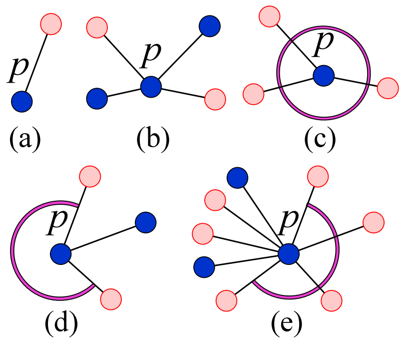

Figure 1: Examples of red-blue point configurations around point p and corresponding magenta angles, α. In a grey-scale output red points appear lighter than blue points. Magenta angles greater than $0°$ are illustrated using arcs of circles. Thus we have angle values (a), (b) $\alpha = 0°$, (c) $\alpha = 360°$, (d), (e) $\alpha > 180°$.

The strategy of reclassification by recolouring, recolours a surrounded point p at each step. Recall that p is surrounded when p has an associated magenta angle that is greater than $180°$. The sequence in which surrounded points are recoloured can be driven by a greedy approach, such as recolouring a point with the largest magenta angle. Alternatively we may recolour surrounded points in an arbitrary manner. The recolouring process stops when there are no more surrounded points.

We use the notation $\overline{pq}$ to denote an edge of the drawing D. For descriptive reasons we sometimes write $\overline{qp}$ to denote the same edge, however, the edges are not directed so both $\overline{pq}$ and $\overline{qp}$ denote the same edge.

Definition2. We say that the edge $\overline{qr}$ is an **opposite edge** of $\overline{pq}$ ($p \neq r$) with respect to q if there is no edge between $\overline{qr}$ and the ray from q that goes in the direction opposite to p.

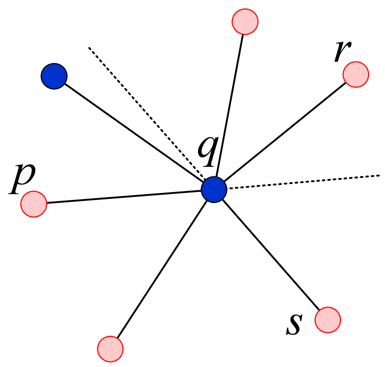

Figure 2: Edges $\overline{qr}$ and $\overline{qs}$ are opposite to $\overline{pq}$. However, $\overline{qp}$ is not opposite to $\overline{sq}$.

For simplification, we omit the "with respect to" qualifier whenever it is clear from the notation. Note that an edge has at most two opposite edges with respect to each endpoint. For example, in Figure 2, both $\overline{qr}$ and $\overline{qs}$ are opposite to $\overline{pq}$. Furthermore, observe the non symmetry of opposites, as $\overline{qp}$ is not opposite to $\overline{sq}$ in the figure.

Definition3. Let q be a surrounded point at the beginning of iteration j of the recolouring sequence, then there exists a maximal consecutive sequence of magenta edges incident to q which we denote by $C_q(j) = (\overline{qp_1}, \overline{qp_2}, \ldots, \overline{qp_k})$. We say that the edges $\overline{qp_1}$ and $\overline{qp_k}$ are **extremal** in $C_q(j)$.

Lemma 1. *For an edge $\overline{pq}$ and any one of its opposite edges with respect to q, $\overline{qr}$, if point q is recoloured, then q receives either the colour of p or the colour of r.*

Proof. [11] Observe that $\overline{pq}$, $\overline{qr}$, or both are in $C_q(j)$. Thus, if q is recoloured it receives the colour of p or the colour of r. □

We continue with an analogue of Lemma 1 when applied to an edge that is extremal in $C_q(j)$.

Lemma 2. *Let q be a surrounded point, at the beginning of iteration j, such that $\overline{pq}$ is extremal in $C_q(j)$ and $\overline{qr}$ is any opposite edge of $\overline{pq}$. Then both p and r are the same colour that is not the colour of q.*

Proof. Since q is surrounded and $\overline{pq}$ is extremal in $C_q(j)$ there is a radial span of more than 180° of magenta edges incident to q beginning at $\overline{pq}$ and containing $\overline{qr}$. Thus $\overline{qr}$ is in $C_q(j)$ and both p and r are the same colour that is not the colour of q. □

Definition4. Let D be a straight-line drawing. An **opposite chain** is a simple path $P = (p_0, \ldots, p_m)$ in D such that

- $p_0 \neq p_m$
- either $\overline{p_i p_{i+1}}$ is opposite to $\overline{p_{i-1} p_i}$ or $\overline{p_i p_{i-1}}$ is opposite to $\overline{p_{i+1} p_i}$, for all $1 < i < m - 1$.

Definition5. Let D be a straight-line drawing. A **monotone chain** is an opposite chain $P = (p_0, \ldots, p_m)$ such that the points are ordered from left (p_0) to right (p_m) by x-coordinate and has maximal length.

In the previous definition, P is not necessarily the longest monotone path from p_0 to p_m, but it is maximal in the sense that no opposite edge can be added to either end of P such that a longer monotone chain is obtained.

3. Recolouring of Triangulations

Recall that a triangulation T of a point set S is a collection of diagonals incident to every point that partitions the interior of the convex hull of S into triangles [9]. Given a coloured triangulation of n points, Reinbacher et al. [11] show that the number of recolourings is finite, in fact at most $2^n - 1$, regardless of the recolouring strategy that is used. They also give an example that following a greedy recolouring scheme results in $\Omega(n^2)$ recolourings. We reproduce this example in Figure 3.

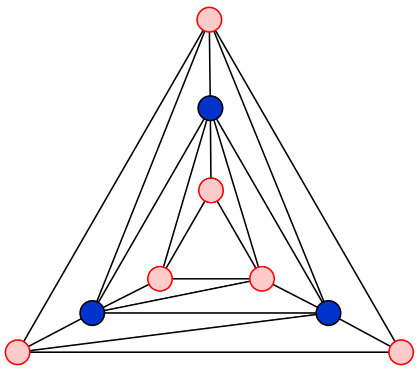

Figure 3: A sequence of recolourings that always recolours a point that is the most nested surrounded point uses $\Omega(n^2)$ recolourings.

Reinbacher et al. also present a number of strategies that always lead to $O(n)$ recolourings. In particular, there is a 2-phase strategy that recolours at most $O(n)$ points: (phase 1) all the surrounded red points are recoloured, (phase 2) all the surrounded blue points are recoloured. The resulting triangulation does not accept any more recolourings since all surrounded red and blue points have already been recoloured. Notice that recolouring blue points (to red) in phase 2 does not create new red surrounded points. However, for red-blue separation purposes, this strategy is not "fair" in the sense that it favours blue. Symmetrically, a red-bias strategy exists. The previous strategy and the $O(n)$ bound also apply to other types of geometric graphs referred to throughout this note. However, in the following we do not refer to a specific strategy but to any, and all, strategies that recolour one surrounded point at a time.

Lemma 3. *A surrounded point q on the convex hull of S can be recoloured at most once.*

Proof. Both convex hull neighbours of q must be in $C_q(j)$. Thus q takes on their colour. Such neighbours of q can no longer become surrounded. This implies that q can be recoloured at most once. □

We define an *internal point* as a point that is not on the boundary of the convex hull of T. Similarly, an *internal edge* is an edge with at least one internal endpoint. Note that the convexity of the faces in the triangulation ensures that for any internal edge $\overline{pq}$ that is incident to an internal point q there always exists at least one opposite edge with respect to q, $\overline{qr}$, such that the points p, q, r appear in x-coordinate order.

We can cover T using a set C of monotone chains as follows. For every edge $\overline{pq}$ in T we can obtain a monotone chain $P_{\overline{pq}}$ starting with edge $\overline{pq}$, then adding edges $\overline{rp}$ and $\overline{qs}$, opposite to $\overline{pq}$. This process is repeated iteratively by inserting opposite edges in both directions from $\overline{pq}$ until the points with smallest and largest x-coordinates are reached. These are obviously points on the convex hull of T. See Figure 4 for an example. Planarity implies that we have $O(n)$ edges in T and, therefore, $O(n)$ chains in C. A similar type of covering of a planar subdivision with monotone chains has been used before by Lee and Preparata [5] with a different purpose.

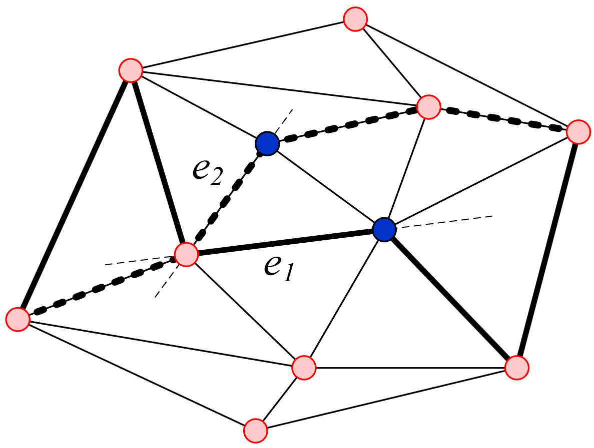

Figure 4: Monotone chains corresponding to the edges e_1 (thick lines) and e_2 (thick dashed lines)

Definition6. Let $P = (p_0, \ldots, p_m)$ be a monotone chain. The **colour-change** number of the chain P, $\chi(P)$, is the number of magenta edges in P. Similarly, the colour-change number of a monotone chain cover C, $\chi(C)$, is defined as the total colour-change number over all chains in C.

Theorem 4. *Given a set of red and blue points, S, together with a triangulation T of S, with $|S| = n$, any recolouring sequence on T will consist of at most $O(n^2)$ recolourings.*

Proof. Consider a cover C of monotone chains for the set of edges of T, and let P be a monotone chain in C. We observe how the colour-change number of C changes with every point recolouring. The analysis is divided into recolourings that occur at the convex hull points, and recolourings that occur at internal points of T. From Lemma 3 it follows that convex hull recolourings can occur at most once per convex hull point. Lemma 1 implies that the colour change number $\chi(P)$ cannot increase when any internal point is recoloured.

We will see that for every recolouring of an internal point, there is always at least one monotone chain whose colour-change number decreases. Suppose that at some step j of the recolouring sequence the internal point q changes colour. If the magenta angle of q is less than 360° we take an extremal magenta edge $\overline{pq}$ in $C_q(j)$; otherwise all edges incident to q are magenta and we choose $\overline{pq}$ arbitrarily. An opposite edge of $\overline{pq}$, $\overline{qr}$, is in the monotone chain $P_{\overline{pq}}$. Furthermore, point r must be the same colour as p and different from q, by Lemma 2. Thus, the colour-change number of $P_{\overline{pq}}$ must decrease by two. See Figure 5.

Obviously, the colour-change number of any monotone chain is at most $n-1$ and can increase (by one) only twice at its endpoints (points on the convex hull with minimum and maximum x-coordinates) during the entire recolouring sequence. Since the number of chains in C is $O(n)$, $\chi(C)$ is $O(n^2)$. This number is not significantly affected (asymptotically) by the possible linear increase of the colour-change number of C at the points of minimum and maximum x-coordinates. On the other hand, every recolouring of an internal point q produces a decrease in $\chi(P_{\overline{pq}})$ for at least one chain $P_{\overline{pq}} \in C$, while the colour-change number for all other chains in C either decreases or remains unchanged. Thus, $\chi(C)$ decreases (by at least two) with the recolouring of an internal point. This proves that at most $O(n^2)$ internal point recolourings can occur. This together with the $O(n)$ number of convex hull point recolourings add up to $O(n^2)$ recolourings, which completes our proof. □

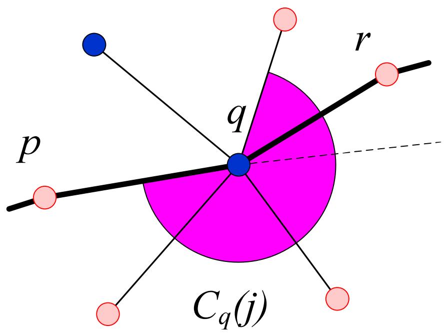

Figure 5: When q is recoloured, the colour change number of the monotone chain $P_{\overline{pq}}$ (thick line) decreases by two. $C_q(j)$ is represented by the shaded area.

4. Recolouring of Straight Line Drawings

In this section we consider more general graphs and their drawings. At all times the graphs are assumed to be connected because, in general, each connected component can be considered independently.

There are families of drawings for which every recolouring sequence is finite and others that allow infinite recolouring sequences. We characterize some of these families, beginning with a class of straight-line drawings with a linear recolouring sequence.

Theorem 5. *Let D be a straight-line drawing with n bi-chromatic points. If D has maximum point degree 3, the length of any recolouring sequence of D is $O(n)$.*

Proof. The proof follows from an observation on how the number of magenta edges decreases with each recolouring. Let p be a point that is being recoloured. At least two edges incident to p need to be magenta, according to the definition of magenta angle. These edges change to a solid colour after the recolouring of p. Before p is recoloured, at most one edge of solid colour can be incident to it, given that $deg(p) \leq 3$. This edge, if it exists, becomes magenta. Therefore, the number of magenta edges decreases by at least one with each recolouring. As the initial number of magenta edges is $O(n)$, the number of recolourings is also $O(n)$. □

The proof of Theorem 5 relies only on the degree of a point. Thus, this bound also holds for non-planar drawings with maximum degree 3. Also, in Section 5 we further extend the scope of this theorem to include non-straight edge drawings.

One may ask whether a recolouring sequence recolours every point at least once. This question is of particular interest for the case of infinite recolouring sequences in planar and non-planar graphs (see Subsection 4.2). The following proposition answers this question, in the negative sense, for drawings with maximum point degree three.

Proposition 6. *Let D be a straight-line drawing with n bi-chromatic points. If D has maximum point degree 3, then no recolouring sequence of D recolours all points.*

Proof. Recall that a point with degree 0 or 1 never gets recoloured. Thus, we assume that all points have degree 2 or 3, or else the theorem is trivially true.

We continue by orienting the edges of the graph. For a point p of degree 2 we orient both incident edges toward p. If the maximum angle formed by the edges incident to a point p of degree 3 is less than or equal to 180° then we orient all 3 edges toward p. Finally for the case where the maximum angle formed by edges incident to p is greater than 180° we orient the two edges forming this angle toward p and the third edge away from p. Observe that with this orientation scheme, if a point p is surrounded, then its incoming edges must be magenta. Furthermore, using this orientation scheme and the fact that a majority of the edges are inward, the pigeon-hole principle implies that there is at least one edge $\overline{pq}$ oriented inward at both p and q. Putting these two observations together we can conclude that in any recolouring scheme only one of p or q can ever be recoloured, thus showing that no recolouring scheme recolours all points. □

4.1. Planar Drawings

One may think of obtaining recolouring bounds for planar graphs based on the fact that a planar graph is a subgraph of a triangulation. However, this is not the case. There are simple examples of a graph G, and a subgraph of G, S, where S has either a larger or a smaller number of recolourings than G in the worst case over all initial colourings.

In fact, a recolouring sequence of a planar graph can be infinite. Figure 6 shows an example of a graph and a colour configuration that may lead to an infinite recolouring sequence (see Appendix A, Figures 10 and 11 for a sequence that repeats a colour configuration). The graph in Figure 6 can be slightly modified and made 2-connected, or the minimum point degree can be increased, without affecting the recolouring sequence, by carefully adding more edges incident to the points of degree one.

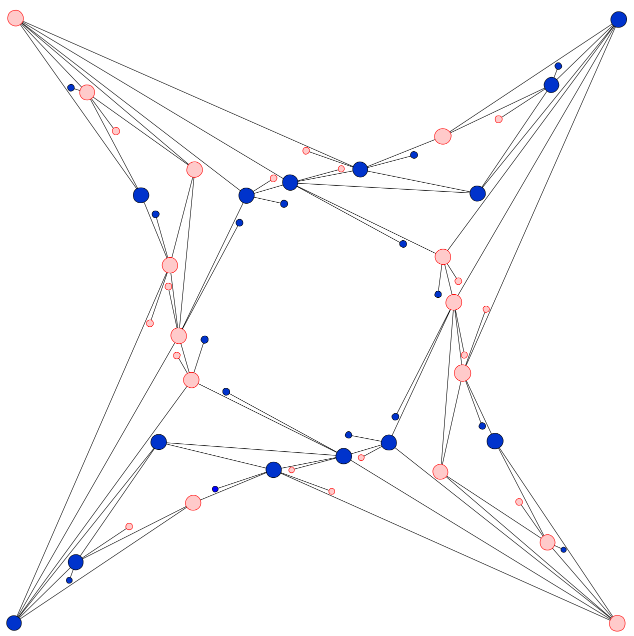

Figure 6: 60 point drawing and initial colouring that leads to an infinite recolouring sequence. See Appendix A for a sequence of recolourings that repeats the initial configuration. Points represented by small disks never change colour.

Notice that the example shown in Figure 6 can also be augmented by attaching other points and edges on the "outside" of any reflex point on the outer face without affecting the infinite recolouring sequence. The recolouring lower bound for planar drawings is generalized in the following theorem.

Theorem 7. *There exist bi-chromatic planar straight-line drawings with 60 or more points that have infinite recolouring sequences.*

Our example in Figure 6 was drawn for clarity of exposition. In fact, we have an examples of planar graphs with smaller number of points that have infinite recolouring sequences. For instance, a 48 point planar drawing with infinite recolouring sequence can be obtained from the example in Figure 6 by carefully merging pairs of points that never change colour and lie on the same face.

Definition7. A **convex point** p of a drawing is a point with two consecutive incident edges, the **convex edges** with respect to p, that define an angle greater than 180°.

Lemma 8. *Let p and q be two convex points that share a convex edge $\overline{pq}$. Edge $\overline{pq}$ cannot change from a solid colour to magenta.*

Proof. Figure 7 depicts the only two different scenarios that comply with the hypothesis of the lemma. It is obvious that a span of an angle greater than 180° around p or q needs to include edge $\overline{pq}$ given the hypothesis of the lemma. Therefore, if $\overline{pq}$ is a solid colour, neither p nor q can be surrounded. □

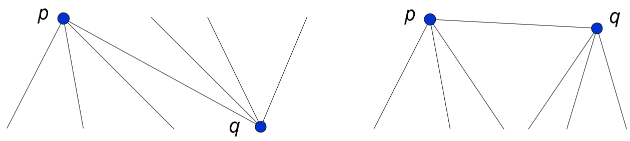

Figure 7: Two cases of adjacent convex points p and q with a convex edge in common.

Theorem 9. *Let D be a planar straight-line drawing with n bi-chromatic points, such that any convex point p_i is connected to another convex point p_j by a convex edge e with respect to both p_i and p_j. A recolouring sequence of D has length $O(n^2)$.*

Proof. The proof of this theorem is similar to the proof of Theorem 4, except for the construction of the cover. In this case the chains in the cover, C, are not necessarily monotone and do not necessarily end at the points with minimum and maximum x-coordinates. However, we construct the chains in a way that maintains their monotonicity (along the x-axis coordinate) whenever possible. Initially, an opposite chain P consists of one edge, the covered edge. Then P is extended in both directions by addition of opposite edges. This way P can be extended (in each direction) until one of the following conditions is met:

- A point of degree one is reached.
- A convex point is reached.

The first case is benign since, by definition, a point of degree one is never surrounded and the colour-change number of an opposite chain can not increase at this point.

For the second case we show how to adjust P such that the colour-change number can increase by one, at most, per endpoint. Let $P = (p_0, \ldots, p_m)$ and let p_0 be a convex point –the following analysis similarly applies to p_m. By the conditions of the theorem, there exists a convex point p adjacent to p_0 such that $\overline{p_0 p}$ is a convex edge. If $p \neq p_1$, we add p to P such that $P = (p, p_0, \ldots, p_m)$; otherwise, P is left unchanged. In either case the first two points of P, let them be p and p_0, or p_0 and p_1, form a pair of convex points connected by a convex edge. Thus, by Lemma 8, the first point of P can change colour at most once. Therefore, the colour-change number of P can increase at most once (by one) at each endpoint.

Thus we have shown that the colour-change number of a monotone chain does not increase significantly. Using this fact we conclude that the number of recolourings is $O(n^2)$ as argued in Theorem 4. □

Definition8. A **convex drawing** is a planar straight-line drawing where all internal faces are convex and the outer face is defined by the convex hull of the set of points.

Corollary 10. *A convex drawing with n bi-chromatic points has $O(n^2)$ recolourings.*

Proof. Notice that the only convex points in a convex drawing are the points on the convex hull and that each one of them is connected to two other points on the convex hull by two convex edges. Thus a convex drawing satisfies the conditions of Theorem 9. It is also noteworthy that a convex drawing has a cover with monotone chains, given that the construction of opposite chains, as in the proof of the theorem, can continue until the points of minimum and maximum x-coordinates are reached. □

For completeness we show that when convex points are adjacent to each other as in the hypothesis of Theorem 9, not all the points can be included in the longest recolouring sequence.

Proposition 11. *Let D be a planar straight-line drawing with n bi-chromatic points, such that any convex point p_i is connected to another convex point p_j by a convex edge e with respect to both p_i and p_j. No recolouring sequence of D recolours all points.*

Proof. Notice that D is finite, and therefore bounded. Thus, there is at least one convex point. By the hypothesis of the theorem, such a convex point is adjacent to another convex point through a convex edge. Lemma 8 shows that two convex points depend on each other: if one of the points changes colour, the other one does not. Thus, one can always find a point that does not change colour. □

4.2. Non-Planar Drawings

At this point, it is obvious that one can also construct non-planar drawings with infinite recolouring sequences since planar drawings allow so. Nevertheless, the examples shown for infinite recolouring sequences on planar drawings include points that never change colour. In Figure 8 we show an example of a non-planar drawing that has an infinite recolouring sequence in which every point changes colour infinitely many times (see Appendix A, Figure 12 for an example infinite recolouring sequence). If similar examples can be built for planar drawings, these have not yet been found.

Notice that the example shown in Figure 8 can be augmented by attaching additional points and edges to any of the existing points towards the “inside” of any of the acute angles without affecting the infinite recolouring sequence.

Theorem 12. *There exist bi-chromatic non-planar straight-line drawings with 16 or more points that have infinite recolouring sequences in which every point changes colour infinitely many times.*

As for the planar case, the infinite recolouring example shown in Figure 8 is not minimal: a 10 point non-planar drawing with infinite recolouring sequence can be obtained from the example in the figure if only 5 pairs of points are used, instead of 8, and edges are slightly changed. For clarity, we do not show a smaller example.

There are also families of non-planar drawings where recolourings always end after a finite number of steps. One such class has already been characterized in Theorem 5. Another class is formally described in the following theorem.

Theorem 13. *Let D be a bi-chromatic non-planar straight-line drawing with set of points S, $|S| = n$, and let CD be a convex drawing also with set of points S. If $CD \subset D$, the length of any recolouring sequence of D is $O(n^3)$.*

Proof. It is known from the proof of Corollary 10 that all recolouring sequences of CD have $O(n^2)$ length and that this can be proved by using a cover with monotone chains. Since $CD \subset D$, it is always possible to cover D with monotone chains as well. This stems from the availability of opposite edges that maintain the monotonicity of the opposite chains at all times. Each monotone chain has $O(n)$ length. The $O(n^2)$ edges of D are assigned one monotone chain each. Therefore, a cover of D with monotone chains has an overall complexity of $O(n^3)$. Thus, the total colour-change number on all monotone chains is also $O(n^3)$. Based on this fact, we conclude that any recolouring sequence of D has $O(n^3)$ length as argued in Theorems 4 and 9. □

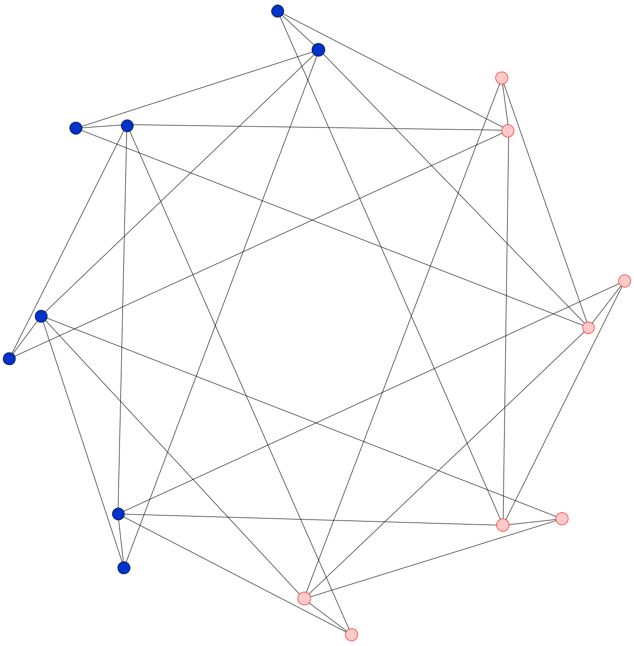

Figure 8: Non-planar drawing and initial colouring that leads to an infinite recolouring sequence. See Appendix A for a sequence of recolourings that repeats the initial configuration.

4.3. Trees

In this subsection we use the term *tree drawing* to refer to a straight-line drawing of a tree (not necessarily planar). A trivial example of a tree drawing that has a $O(n)$ recolouring sequence is a "jigsaw" path with points alternately coloured. In such an example, all blue points can be coloured to red, leading to approximately $n/2$ recolourings.

An argument similar to the proof of Theorem 9 can be made in order to prove a quadratic upper bound on the number of recolourings of tree drawings, with the difference that chains need not be monotone. Such chains (consisting of opposite edges) will always end at points of degree one (leaves) given the absence of cycles. Consequently, the colour change of one such chain never increases, thus the overall number of recolourings is bounded by $O(n^2)$.

As a corollary of Theorem 5 it follows that binary tree drawings have a linear number of recolourings. In this section we prove that the number of recolourings of tree drawings is also linear.

In order to prove a tight bound (Theorem 16) on the number of recolourings of tree drawings, we define a partial order on the recolourings involved in a recolouring sequence. We then bound the total number of recolourings based on the number of minimal elements (sinks) of such a partial order. This idea is explained and formalized in the remainder of this section.

We denote a recolouring event r, or simply a recolouring, as the event of a certain point p being recoloured. Let $R = (r_1, \ldots, r_k)$ be a recolouring sequence in which r_i denotes the recolouring at step i, $1 \leq i \leq k$, $k > 0$. We also denote $p(r_i)$ as the point that changes colour at recolouring r_i, and $N(r_i)$ the number of times that $p(r_i)$ has changed colour in R prior to event r_i.

Definition9. Let T be a tree drawing and let R be a recolouring sequence of T. The **history graph** of R is a directed graph $H = (R, I)$, $I \subset R \times R$ such that $(r_j, r_i) \in I$ if and only if there exists $r \in R$, such that $\overline{p(r)p(r_j)} \in C_{p(r_j)}(j)$, and $i = max(\{l : 1 \leq l < j, p(r_l) = p(r)\})$.

In simple words, the history graph of a given recolouring sequence contains all the recolourings as vertices and certain dependencies among the recolourings as edges. More specifically, there exists an edge from recolouring r_j to recolouring r_i if and only if r_i is the last recolouring of a neighbour $p(r_i)$ of $p(r_j)$ prior to r_j, such that $p(r_i)$ is in the magenta angle associated to r_j. See Figure 9 for an example. Notice that, according to the previous definition, for any two recolourings, r_i, r_j, such that $(r_k, r_i) \in I$ and $(r_k, r_j) \in I$, $p(r_i) \neq p(r_j)$.

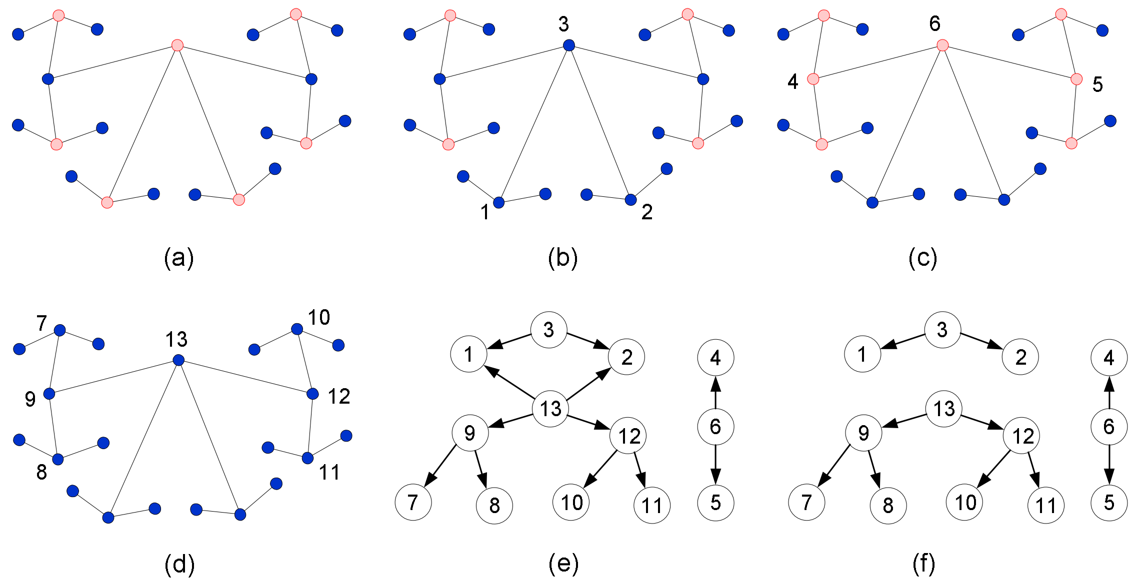

Figure 9: Example tree with recolouring sequence $R = \{r_1, \ldots, r_{13}\}$. (a) original configuration; (b), (c), (d) different stages along the recolouring sequence –the indices of the recolourings appear as labels at the corresponding points–; (e) history graph of R; (f) binary history graph of R.

Observation 1. *By the definition of history graph all the edges are directed from later recolourings to earlier ones. Therefore, a history graph is a directed acyclic graph (DAG) and defines a partial order on the elements of the recolouring sequence.*

The following lemma proves that there are at least two neighbours of a point p that are recoloured at least once between two consecutive recolourings of p.

Lemma 14. *Let T be a tree drawing with n bi-chromatic points, let R be a recolouring sequence of T, and let $H = (R, I)$ be the history graph of R. Consider a recolouring $r \in R$ with $N(r) > 0$. Then the outdegree of r is at least 2.*

Proof. Obviously, if a point is recoloured red (or similarly blue) and was recoloured earlier in the sequence, the previous recolouring was to blue (red). The intersection between the magenta angles at the time it is surrounded by red (blue) and previously by blue (red) contains at least two edges because the corresponding magenta angles are greater than 180°. Therefore, there are at least two neighbours of p, $p_1, p_2 \in T$, that are recoloured at least once between two consecutive recolourings of p. □

In the light of Lemma 14, we can state the following definition.

Definition10. Let R be a recolouring sequence of a tree drawing T and $H = (R, I)$ be the corresponding history graph. The **binary history graph** of R, $BH = (R, BI)$, $BI \subseteq I$, is a subgraph of the history graph where nodes have outdegrees 2 or 0: nodes with outdegree 0 correspond to first time recolourings; nodes with outdegree 2 correspond to subsequent recolourings. Consider a node r_k such that $N(r_k) > 0$, that is, a recolouring of a point that has been previously recoloured. We choose the two outgoing edges of r_k, (r_k, r_i), (r_k, r_j), such that i and j are the largest indices smaller than k for neighbours of r_k in the history graph.

The motivation to define the binary history graph is to obtain a cycle free subgraph of the history graph that involves all the recolourings (see Figure 9 (f)). In the next lemma we prove that the binary history graph is, in fact, cycle free.

Lemma 15. *Let T be a tree drawing, and R a recolouring sequence of T with binary history graph BH. BH has no directed or undirected simple cycles. Therefore, BH is a forest of trees.*

Proof. Since BH is a subgraph of the history graph of R, BH is also a DAG, by Observation 1. Therefore, there are no directed cycles in BH. Any undirected simple cycle BH would have at least one node r with two outgoing edges and one node s with two incoming edges. For the sake of contradiction, we assume that there exists such a simple cycle, C, in BH.

Consider the function $f : R^* \to V(T)^*$ such that $f(r_1, r_2, \ldots, r_k) = p(r_1), p(r_2), \ldots, p(r_k)$, $r_i \in R, 1 \leq i \leq k$. In particular, f maps a path in BH to a path in T. Let P_1 and P_2 be the two undirected paths that connect r and s in C. By the definition of binary history graph, the outgoing edges of r are incident to nodes t_1 and t_2 such that $p(t_1) \neq p(t_2)$. Thus, $|C| > 2$. Without loss of generality, let t_1 be in P_1 and t_2 be in P_2. Then paths $f(P_1)$ and $f(P_2)$ are different at points $p(t_1)$ and $p(t_2)$. This implies that there are two different paths in T connecting $p(r)$ and $p(s)$. Thus, we establish a contradiction. □

To obtain a bound on the size of binary history graphs we show that the number of nodes is linear in the size of the corresponding tree drawing. This will lead us to conclude the results of the following theorem.

Theorem 16. *Let T be a tree drawing with n bi-chromatic points. The length of any recolouring sequence of T is $O(n)$.*

Proof. Let R be any recolouring sequence of T, let BH be the binary history graph of R, and let V and E be the set of nodes and edges of BH, respectively. In order to prove this theorem we show that $|V| = |R|$ is $O(n)$. Let V_k denote the set of nodes of degree k in V, and V_{k^+} the set of nodes of degree at least k in V. For accounting purposes, we partition the set of nodes of BH into four classes: V_0, V_1, V_2, and V_{3^+}.

Nodes of degree 0 and 1 are all first-time recolourings (sinks) according to the definition of binary history graph, because they have 0 outgoing edges. Also, every node of degree 2 is either a sink or a source because internal nodes have degree at least 3, that is, one or more incoming edges and two outgoing edges. We partition the set of degree-2 nodes into V_2^t, the sinks of degree 2, and V_2^s, the sources.

Next we show that the binary history graph has less sources than non-source nodes (i.e., $|V_2^s| < |V \setminus V_2^s|$). Suppose, for the sake of contradiction, that $|V_2^s| > |V \setminus V_2^s|$). Let $k = |V_2^s|$ be the number of sources. Because there are 2 distinct edges incident to each source, the overall number of edges in BH satisfies $|E| \geq 2k$. Given that BH is a forest of trees, $|E| = |V| - m$, where $m > 0$ is the number of connected components of BH. It follows that $|V| > 2k$. Therefore, $|V \setminus V_2^s| > k = |V_2^s|$, which contradicts the original assumption. We use the new bound on the number of sources to derive the following equations.

$$|V| = |V_0| + |V_1| + |V_2^s| + |V_2^t| + |V_{3^+}| \leq 2(|V_0| + |V_1| + |V_2^t| + |V_{3^+}|). \tag{1}$$

Notice that at most n nodes can be sinks since in the worst case all points in T are recoloured for the first time. Consequently,

$$|V_0| + |V_1| + |V_2^t| \leq n. \tag{2}$$

Thus, a linear bound on $|V_{3^+}|$ entails a linear bound on $|V|$. We derive such bound in what follows. From properties of graphs and, in particular, of forests of trees, and from Equation (1),

$$\sum_{r \in V} deg(r) = 2|E| < 2|V| - 2m < 2(|V_0| + |V_1| + |V_2| + |V_{3^+}|), \tag{3}$$

According to the definitions of V_k and V_{k^+},

$$\sum_{r \in V} deg(r) \geq |V_1| + 2|V_2| + 3|V_{3^+}|. \tag{4}$$

Equations (3) and (4) lead to

$$|V_{3^+}| \leq 2|V_0| + |V_1| - 2m. \tag{5}$$

Observe that the number of nodes of degree 0 cannot be greater than the number of connected components. Thus, it follows that $|V_0| \leq m$ and $|V_{3^+}| \leq |V_1|$. Combining this with (2) we obtain

$$|V_{3^+}| \leq n. \tag{6}$$

Finally, from (1), (2), and (6) we have

$$|V| \leq 2(|V_0| + |V_1| + |V_2^t| + |V_{3^+}|) \leq 4n \tag{7}$$

Thus, we conclude that the length of any recolouring sequence of T is at most $4n$, or $O(n)$. □

5. Extensions

5.1. Non-straight Edges

Recolourings may also occur in non-straight line drawings. One can consider a point as surrounded whenever the magenta angle defined by the tangents of a set of consecutive magenta edges leaving the point is greater than 180°. Theorem 5 also holds in this case, that is, any non-straight line drawing with minimum point degree 3 has a recolouring sequence of length at most $O(n)$. However, for more general graphs the results seem to differ from straight line drawings. Figure 13 in Appendix A shows a simple example of a planar graph where the edges have at most one bend and there is a recolouring sequence in which all the points change colour infinitely many times.

5.2. More Than Two Colours

Suppose that the points come in more than two colours. We define the colour of an edge as the mixture of the colours of its endpoints. In a multicoloured scenario we say that p is *surrounded* by a set of edges of a single mixed colour if the edges define a continuous angle greater than 180°. As we may intuitively observe, increasing the number of colours only lowers the chances of a point being surrounded without changing the fundamental nature of the problem. In fact, inspection shows that all of our previous definitions and results hold in a multicoloured scenario. Thus, our recolouring bounds for a bi-chromatic set of points carries over to multicoloured point sets.

6. Conclusions and Future Work

We have re-examined a point recolouring method useful for reclassifying points to obtain reasonable subdividing boundaries. We show tight bounds for point recolouring in triangulations, trees, and graphs of maximum degree 3 for the longest possible recolouring sequences. In contrast, there are examples of finite planar graphs that allow for infinitely many recolourings.

Some interesting questions remain open. First, can planar drawings have sequences of recolourings in which all the points change colour infinitely many times? Another interesting issue is the existing gap between the lower bound ($\Omega(n^2)$) for the number of recolourings in non-planar graphs that contain a convex drawing of the set of points –this bound is provided by the example in Figure 3– and the upper bound ($O(n^3)$) provided in Theorem 13.

7. Acknowledgements

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A. Infinite Recolouring Sequence on Different Types of Straight-Line Drawings

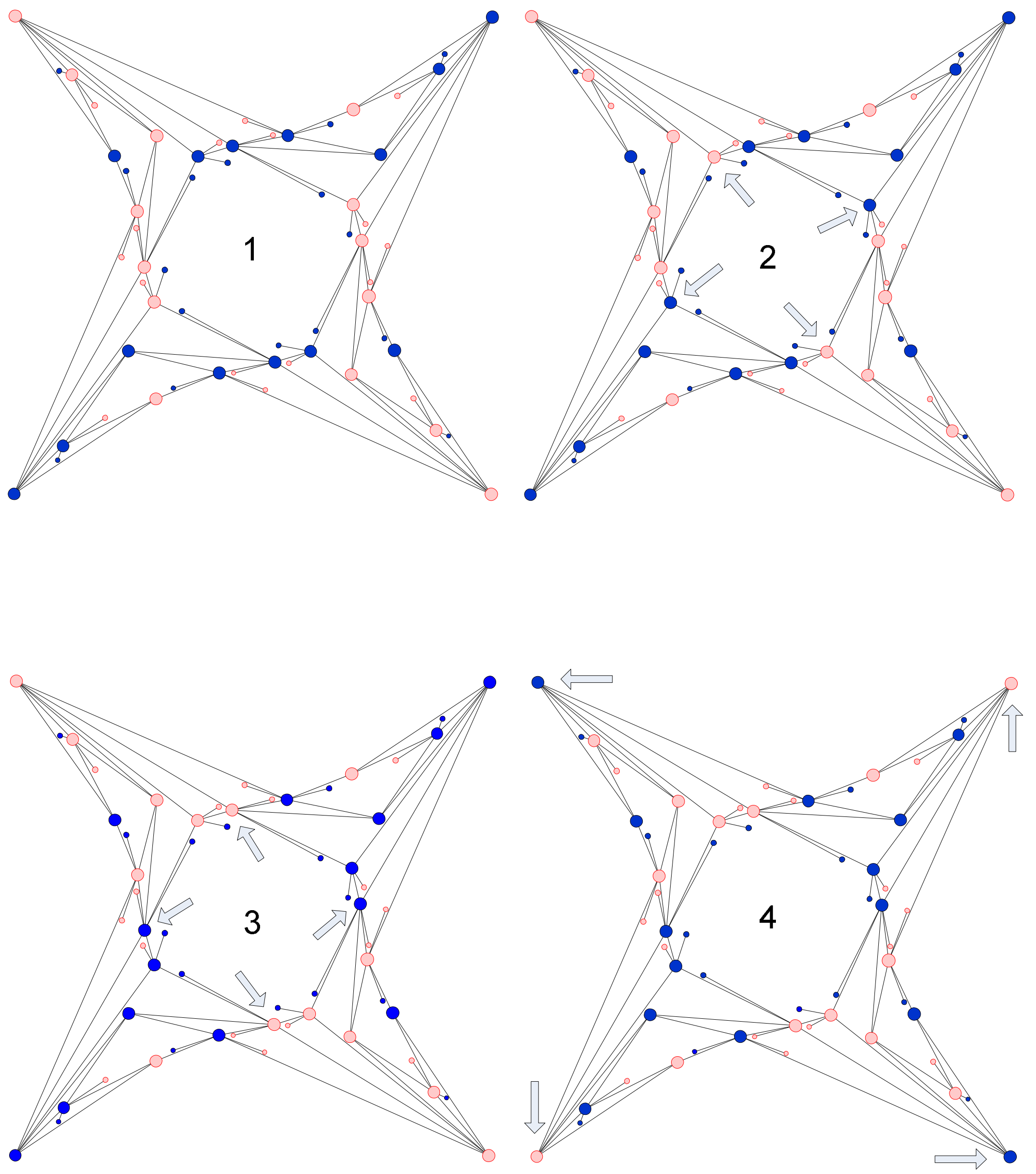

Figure 10: Infinite recolouring sequence of a planar drawing (Part I). Points represented by small disks never change colour. Recoloured points are pointed out by arrows. The recolourings occur one at a time. The recolouring sequence continues in Figure 11.

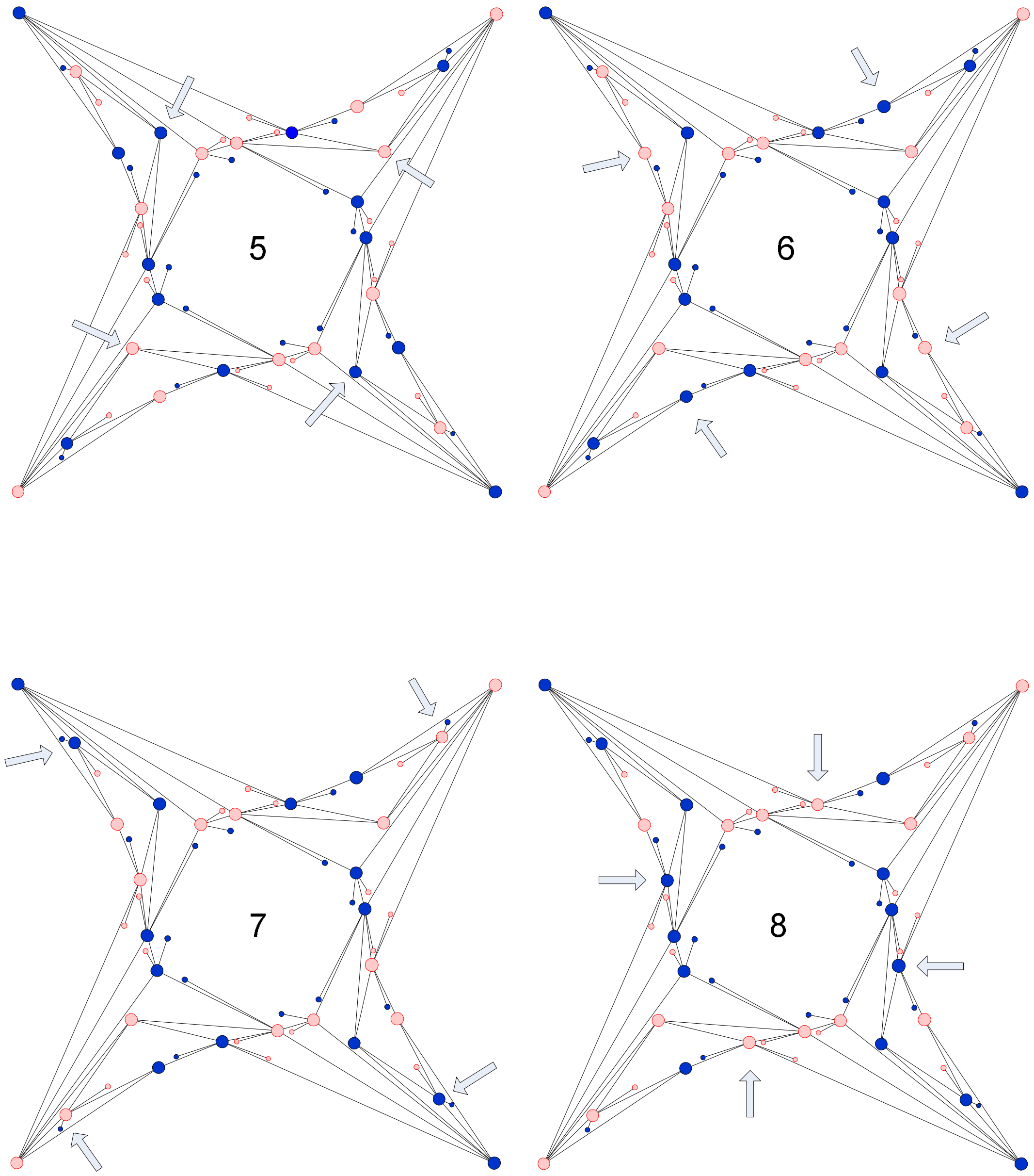

Figure 11: Infinite recolouring sequence of a planar drawing (Part II). Points represented by small disks never change colour. Recoloured points are pointed out by arrows. The recolourings occur one at a time. Notice that drawing 8 is a rotation of drawing 1 in Figure 10.

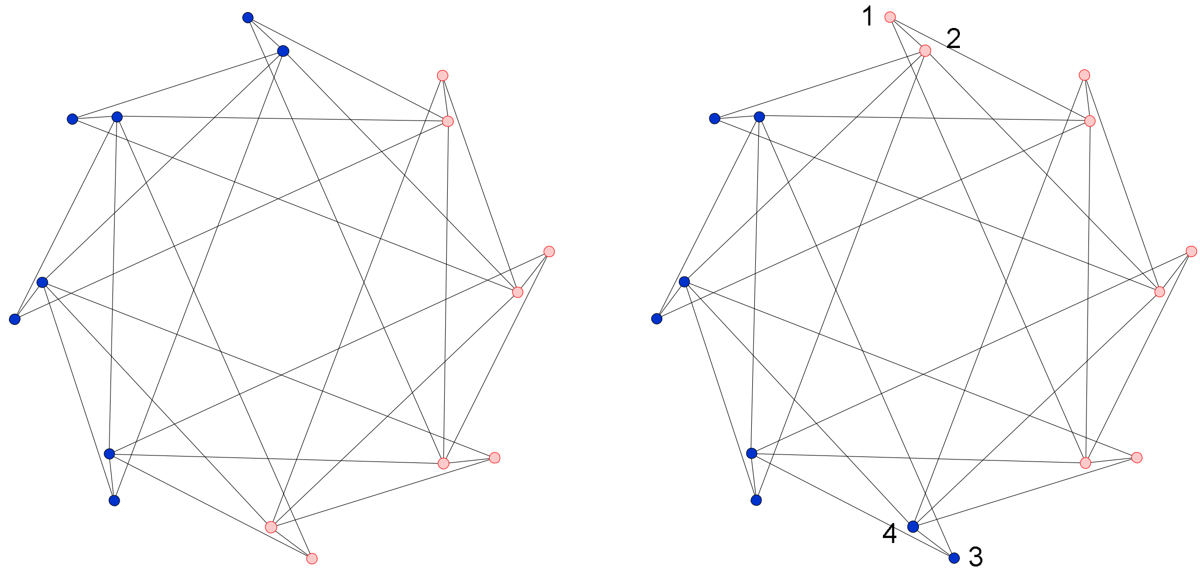

Figure 12: Infinite recolouring sequence of a non-planar drawing. Recolourings occur in the order indicated by the numbers. Notice that the figure on the right is a rotation of the figure on the left.

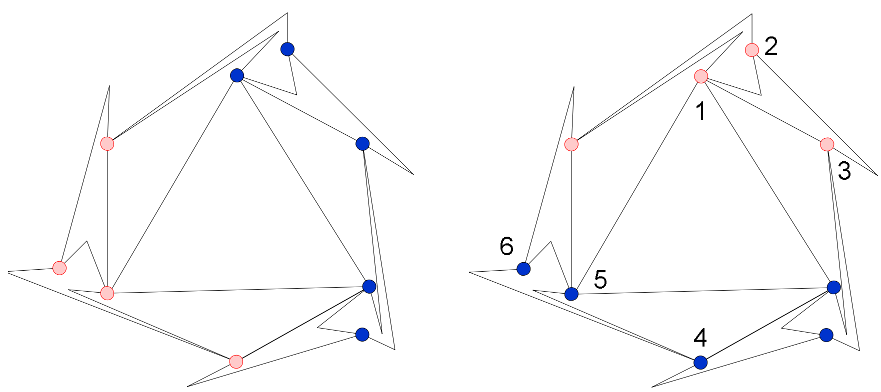

Figure 13: Infinite recolouring sequence of a planar graph with a 1-bend drawing. Recolourings occur in the order indicated by the numbers. Notice that the figure on the right is a rotation of the figure on the left.