

# Implementing Path Coloring Algorithms on Planar Graphs

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## Abstract

A path coloring of a graph partitions its vertex set into color classes such that each class induces a disjoint union of paths. In this project we consider implementing several algorithms to compute path colorings of graphs embedded in the plane.

We present two algorithms to path color plane graphs with 3 colors based on a proof by Poh's in 1990. First we describe a naive algorithm that directly follows Poh's procedure, then we give a modified algorithm that runs in linear time.

Independent results of Hartman and Skrekovski describe a procedure that takes a plane graph  $G$  and a list of 3 colors for each vertex, and computes a path coloring of  $G$  such that each vertex receives a color from its list. We present a linear time algorithm based on Hartman and Skrekovski's proofs.

A C++ implementation is provided for all three algorithms utilizing the Boost Graph Library.

## 1 Plane Graphs

We will be concerned only with simple plane graphs. Informally, a plane graph is a network drawn in the plane consisting of a set of points, and a set of lines between points such that no lines cross.

Formally a *simple graph* is a pair  $G = (V, E)$  consisting of a finite set  $V$  of *vertices* and a set  $E$  of two element subsets of  $V$  known as *edges*. We will refer to the the vertex and edge sets of a graph  $G$  by  $V(G)$  and  $E(G)$ , respectively. All graphs in this project are simple.

As shorthand we will denote an edge  $\{u, v\} \in E(G)$  simply as  $uv$  or  $vu$ . Furthermore, if it is clear by context that  $v \in V(G)$  is a vertex, or  $uv \in E(G)$  an edge, we will use the notation  $v \in G$ , or  $uv, \in G$ .

Two vertices  $u, v \in V(G)$  are *adjacent* if  $uv \in E(G)$ . Vertices  $u$  and  $v$  are known as the *endpoints* of  $uv$ . The edge  $uv$  is said to be *incident* to the vertices  $u$  and  $v$ .



Figure 1.1: Drawings of  $K_3$ ,  $K_4$ ,  $K_5$  (nonplanar), a length 4 path, and a 6-cycle.

The vertices in  $G$  adjacent to a vertex  $v$  are known as the *neighbors* of  $v$ . The number of neighbors of a vertex  $v$  is its *degree*, denoted  $\deg(v)$ .

A graph  $H$  is a *subgraph* of  $G$  if  $V(H) \subseteq V(G)$  and  $E(H) \subseteq E(G)$ . If  $S \subseteq V(G)$  the *induced subgraph* of  $S$  on  $G$  is the subgraph  $H$  defined by  $V(H) = S$  and  $E(H) = \{uv \in E(G) \mid u, v \in S\}$ . We say a subgraph  $H$  of a graph  $G$  is *induced* if it is the induced subgraph of its vertex set on  $G$ .

If  $v \in V(G)$  we will use  $G - v$  to denote the subgraph obtained by removing  $v$  and its incident edges from  $G$ . Similarly, if  $H$  is a subgraph of a graph  $G$ , we define  $G - H$  to be the subgraph obtained by removing from  $G$  all vertices in  $H$  and all edges incident to a vertex in  $H$ .

A length  $n$  path consists of the vertices  $v_1, v_2, \dots, v_n$  and the edges  $v_1v_2, v_2v_3, \dots, v_{n-1}v_n$ . A length  $n$  cycle, or  $n$ -cycle, consists of a length  $n$  path and the additional edge  $v_1v_n$ . We will often denote a path or cycle  $G$  by simply listing its vertices in order, i.e.  $G = v_1v_2 \dots v_n$ .

If a path  $P = v_1v_2 \dots v_n$  is a subgraph of a graph  $G$ , we say  $P$  is a  $v_1v_n$ -*path* in  $G$ . A graph  $G$  is *connected* if for every  $u, v \in V(G)$ , there exists a  $uv$ -path in  $G$ . If any  $k$  vertices may be removed from a graph  $G$  with  $G$  remaining connected, we say  $G$  is  $k$ -*connected*.

In all figures a dashed line between a pair of vertices  $u, v \in G$  will represent a  $uv$ -path in  $G$ .

A *drawing* of a graph maps each vertex to a point in the plane and each edge to a curve connecting its endpoints. A *planar embedding* is a drawing where edge curves intersect only at their endpoints. We say a graph is *planar* if it admits a planar embedding. A planar graph together with a particular planar embedding is called a *plane graph*.

Let  $G$  be a plane graph. A *face* of  $G$  is a maximal region of the plane not containing any point used in the embedding. The unbounded face is known as the *outer face*. We will always refer to a face by the subgraph of vertices and edges that lie on its border.

For brevity, we have not fully formalized curves, regions, or borders. However, the above definitions and results are fairly standard and may be found in many graph theory texts, for example [25].

**Theorem 1.1** (Euler's Formula). *If  $G$  is a connected plane graph with  $n$  vertices,  $m$*

edges, and  $f$  faces, then  $n - m + f = 2$ .

A simple corollary of Euler's Formula states that if  $n \geq 3$ , then  $m \leq 3n - 6$ . A planar graph is said to be *triangulated* if adding any new edge results in a nonplanar graph. Triangulated plane graphs with  $n \geq 3$  vertices have exactly  $3n - 6$  edges.

A face is said to be a *triangle* if it is a 3-cycle. It is easy to see that all faces in a triangulated plane graph are triangles: if any face has more than three vertices then we may add an edge curve connecting two face vertices without crossing existing edges. Conversely if all faces in a plane graph are triangles, then it is triangulated.

If a plane graph has triangles for all but one face we shall say it is *weakly triangulated*. We will always assume the non-triangle face is the outer face. A 2-connected weakly triangulated plane graph has a cycle for its nontriangle face.

Suppose  $C$  is a cycle in a weakly triangulated plane graph  $G$ . Then the subgraph consisting of  $C$  and all interior vertices and edges is denoted  $\text{Int}(C)$ . If  $u, v \in V(C)$  then we denote the  $uv$ -path in  $C$  running clockwise around the cycle with  $C[u, v]$ . Finally, if  $u, v \in V(C)$  we call any edge  $uv \in E(G) \setminus E(C)$  a *chord* of the cycle  $C$ .

A *rotation scheme* for a graph is a cyclic ordering of the incident edges around each vertex. Planar embeddings naturally induce a rotation scheme by the counterclockwise order in which edge curves are positioned around each vertex. In fact, with respect to graph algorithms, the induced rotation scheme contains all the useful information of an embedding. Therefore, while we may often visualize plane graphs with drawings, planar embeddings will always be represented solely by their induced rotation scheme.

## 2 A Brief History of Coloring Plane Graphs

A  $k$ -coloring of a graph maps each vertex to one of  $k$  possible colors. Equivalently, a  $k$ -coloring partitions the vertices of a graph into  $k$  disjoint sets called *color classes*. A coloring is *proper* if no pair of adjacent vertices receive the same color, or equivalently if the color classes all consist of nonadjacent vertices.

It is clear that not all planar graphs admit a proper 3-coloring: the complete graph on four vertices is planar and requires 4 colors. Whether all planar graphs admit a proper coloring with 4 colors, the Four Color Problem, remained one of the premier open questions in graph theory until it was verified by Appel and Haken in 1976 [1, 2].

A  $(k, l)$ -coloring, or a  $k$ -coloring with defect  $l$ , is a  $k$ -coloring such that each vertex has at most  $l$  same color neighbors. Generalizations of proper colorings were first introduced in 1968 by Chartrand et al. in [7]. Defective colorings in particular were introduced about simultaneously around 1985 by Cowen et al. [10], Jones et al. [16], and Jacobson et al. [3]. It was shown in [10] that all planar graphs admit a  $(3, 2)$ -coloring.

A *path  $k$ -coloring* is a  $k$ -coloring such that the induced subgraph of each color class consists of one or more disjoint paths. Note that path  $k$ -coloring is equivalent

to  $(k, 2)$ -coloring with the added restriction that path coloring forbids cycles. It was conjectured by Broere et. al. [6] that all planar graphs may be path 3-colored. In 1990 Poh [19] and Goddard [14] independently proved the conjecture. Planar graphs that do not admit a path 3-coloring were described by Chartrand et. al. [9], and thus the result is best possible.

Poh's proof is constructive and may easily be adapted to an algorithm for path 3-coloring plane graphs. Here we describe a naive version of Poh's algorithm, as well as a modified algorithm that runs in  $\mathcal{O}(n)$  time.

Let  $G$  be a graph. A *list assignment* for  $G$  is a map  $L$  assigning each vertex  $v \in V(G)$  a list of colors. Given a list assignment  $L$  an  *$L$ -list-coloring* of  $G$ , first introduced by Erdős et al. in [12], maps each  $v \in V(G)$  to a color in  $L(v)$ . We say a graph  $G$  is  *$k$ -choosable* if given any list assignment  $L$  such that  $|L(v)| \geq k$  for all  $v \in V(G)$ ,  $G$  admits a proper  $L$ -list-coloring.

In 1994 Thomassen [23] proved that if  $G$  is planar, then  $G$  is 5-choosable. A planar graph that is not 4-choosable was described by Voigt [24] in 1993, so Thomassen's result is best possible.

We may equivalently define the properties  *$(k, l)$ -choosable* and *path  $k$ -choosable*. In 1997 Hartman [17] proved that all planar graphs are path 3-choosable. Hartman's result is best possible since path 3-coloring is a special case of path  $L$ -list-coloring with lists of size 3. In 1999 Hull and Eaton [11] and Skrekovski [22] independently proved that if  $G$  is a planar graph, then  $G$  is  $(3, 2)$ -choosable.

Hartman's proof provides a constructive procedure to construct a path  $L$ -list-coloring for a plane graph that has been given a list assignment  $L$  with lists of size at least 3. Interestingly, the proofs of Hartman and Skrekovski follow the same coloring algorithm, and thus Skrekovski unknowingly showed the stronger path 3-choosability result. We describe an algorithm based on Hartman and Skrekovski's work and show it runs in  $\mathcal{O}(n)$  time.

### 3 Graph Representations and Time Complexity

Let  $G$  be a plane graph. Vertices will be represented by integers, that is, we shall assume  $V(G) = \{0, 1, \dots, n-1\}$ . We will always denote number of vertices in  $G$  with  $n$  and the number of edges with  $m$ .

The input size for each algorithm, given input graph  $G$ , will be the number of vertices  $n$ . However, since  $G$  is a plane graph, if  $n \geq 3$  then  $m \leq 3n - 6$ . Thus  $\mathcal{O}(m) = \mathcal{O}(n)$ . Hence it is equivalent to take the input size to be the number of edges  $m$ .

We assume an integer RAM model of computation in which integers require fixed space and integer operations take constant time. The basic operation for all time complexity discussions will therefore be a single memory reference lookup, integer arithmetic operation, or integer comparison.

We will ignore the allocation of memory with respect to time complexity, such as in the creation of arrays or other data structures. The operations required to initialize elements in a structure are counted. In accordance with these assumptions, inserting or removing an element in a linked list or at the back of an array will require  $\mathcal{O}(1)$  time.

Vertex properties will be stored in size  $n$  arrays indexed by vertices. Thus accessing or comparing vertex properties shall, in general, be constant time. Colors are assumed to be integers. A coloring of  $G$  will thus be represented by an integer vertex property.

For each  $v \in V(G)$  we define a linked list called an *adjacency list* containing the neighbors of  $v$  ordered according to the rotation scheme of the embedding. The full plane graph  $G$  may then be represented by a vertex property  $\text{Adj}$  storing the adjacency list for each vertex. That is, each vertex  $v \in V(G)$  has the adjacency list  $\text{Adj}[v]$ .

We will sometimes wish for the ability to quickly find a neighbor  $u$  in  $v$ 's adjacency list directly from  $v$ 's entry in  $u$ 's list. To allow this lookup in  $\mathcal{O}(1)$  time we will instead define a linked list of pairs  $\text{Adj}[v]$  for each  $v \in V(G)$  called an *augmented adjacency list*. Each node in the list  $\text{Adj}[v]$  will store a neighboring vertex  $u$  as well as a reference to the node for  $v$  in  $\text{Adj}[u]$ .

An augmented adjacency list representation of a graph  $G$  may be constructed from a standard adjacency list representation in  $\mathcal{O}(m)$  time via the following algorithm due to Glenn Chappell.

**Algorithm 3.1.** (Augment Adjacency Lists)

**Input:** An adjacency list representation  $\text{Adj}$  of a graph  $G$ .

**Output:** An augmented adjacency list representation  $\text{Adj}'$  of  $G$  with the neighbors of each vertex listed in the same order as in  $\text{Adj}$ .

**Description:** We will begin by using  $\text{Adj}$  to construct an augmented adjacency list representation  $\text{Adj}'$  of  $G$  with the reference portion of each node uninitialized. Next we construct an array  $\text{Wrk}[v]$  of size  $\deg(v)$  for each  $v \in V(G)$ .

We fill in  $\text{Wrk}$  as follows. For each  $v$  from 0 to  $n - 1$  let us walk through  $\text{Adj}'[v]$ . At each neighbor  $u$  in  $\text{Adj}'[v]$  let  $r_{v,u}$  be the reference to  $u$ 's position in  $\text{Adj}'[v]$  and append the pair  $(v, r_{v,u})$  to  $\text{Wrk}[u]$ .

After this process finishes each  $u \in V(G)$  will have an array  $\text{Wrk}[u]$  containing the pairs  $(v, r_{v,u})$  for each neighbor  $v$ , sorted in ascending order by the vertices  $v$ .

We will now initialize the references of each node of the augmented adjacency lists. Iterate through the vertices in descending order. Let  $v$  be the current vertex. For each  $uw \in E(G)$  such that  $u < w$  and  $v < w$  we shall have initialized the reference for  $u$  in  $\text{Adj}'[w]$  and the reference for  $w$  in  $\text{Adj}'[u]$ . We will also have removed the entry  $(w, r_{w,u})$  from  $\text{Wrk}[u]$ . It remains to handle edges  $uv \in E(G)$  with  $v > u$ .

For each  $v$  from  $n - 1$  to 0 let us walk through  $\text{Wrk}[v]$ . For  $i$  from 1 to  $\deg(v)$  take  $(u, r_{u,v}) = \text{Wrk}[v][i]$ . Note  $u < v$  by our assumptions above. Moreover,  $\text{Wrk}[u]$  contains no entries for neighbors greater than  $v$  so  $(v, r_{v,u})$  is the last element of  $\text{Wrk}[u]$ . Thus we may lookup  $r_{v,u}$  to find  $u$ 's node in  $\text{Adj}'[v]$  and initialize the reference

with  $r_{u,v}$ . We may similarly initialize the reference for  $v$ 's node in  $\text{Adj}'[u]$ . Finally, we remove  $(v, r_{v,u})$  from  $\text{Wrk}[u]$ .

**Time Complexity:** For each edge  $uv \in E(G)$ ,  $u < v$ , we make a constant number of assignments to  $\text{Adj}'$  and  $\text{Wrk}$ , two reference lookups, and one entry removal from the back of  $\text{Wrk}[u]$ . Therefore the overall complexity of the algorithm is  $\mathcal{O}(m)$ .

If  $G$  is a planar graph without a given embedding we may still construct an adjacency list representation of  $G$ , with neighbors simply listed in arbitrary order. There exist numerous algorithms to then simultaneously find an embedding of  $G$  and construct an embedding ordered adjacency list representation of the corresponding plane graph in  $\mathcal{O}(n)$  time [18, 8, 5, 4]. Additionally, there exist  $\mathcal{O}(n)$  algorithms to add edges to the adjacency list representation in order to connect, 2-connect, or triangulate  $G$  while maintaining planarity [15, 20, 13]. Thus while the algorithms presented will often assume that input graphs are triangulated and plane embedded, arbitrary planar graphs may be modified in linear time to fit these criteria.

Each algorithm presented in this project will allocate some fixed number of vertex properties, independent of the size of the graph. The size of all other data structures constructed will be  $\mathcal{O}(n)$  at all points during the operation of each algorithm. Therefore the size complexity of every algorithm is  $\mathcal{O}(n)$ .

Some algorithm entries, for example *Poh 3-Coloring* (4.1), will describe procedures on abstract graphs. Others, for example *Augment Adjacency Lists* (3.1) below, will describe algorithms working with computer graph representations. We will provide time complexity analysis for all algorithms working with concrete representations.

## 4 Path Coloring and the Poh Algorithm

In this section we detail two algorithms for path 3-coloring plane graphs. We begin by describing the general procedure proposed by Poh [19].

**Algorithm 4.1.** (Poh 3-Coloring)

**Input:** A 2-connected weakly triangulated plane graph  $G$  with outer cycle  $C = v_1v_2 \dots v_k$  and a 2-coloring of  $C$  such that the color classes induce the paths  $P = v_1v_2 \dots v_l$  and  $Q = v_kv_{k-1} \dots v_{l+1}$ .

**Output:** We find an extension of the 2-coloring of  $C$  to a path 3-coloring of  $G$  such that no vertex in  $C$  receives a same color neighbor in  $G - C$ .

**Description:** If  $G - C$  is empty there are no vertices remaining to color. Otherwise the algorithm proceeds as follows.

*Case 1:* Suppose there is a chord of  $C$ , that is, an edge  $v_iv_j \in E(G) \setminus E(C)$  with  $i < j$ . Since  $P$  and  $Q$  are induced paths it must be that  $v_i \in P$  and  $v_j \in Q$ . Let  $C_1$  be the cycle consisting of  $C[v_j, v_i]$  and the edge  $v_iv_j$ , and  $C_2$  the cycle consisting of  $C[v_i, v_j]$  and the edge  $v_iv_j$ . Observe  $C_1$  and  $C_2$  are each 2-colored such that each color class induces a path. Thus we may apply the algorithm to path 3-color  $\text{Int}(C_1)$



Figure 4.1: The case of a chord (left) and the case no chord exists (right).

and  $\text{Int}(C_2)$ . Since the subgraphs  $\text{Int}(C_1)$  and  $\text{Int}(C_2)$  have only the vertices of the chord  $v_i v_j$  in common, the combined coloring forms a path 3-coloring of  $G$ .

*Case 2:* Suppose no chords of  $C$  exist. Let  $u$  be the neighbor of  $v_k$  immediately clockwise from  $v_1$  and let  $w$  be the neighbor of  $v_l$  immediately clockwise from  $v_{l+1}$ . That is,  $u, w \in \text{Int}(C)$  are the unique, but possibly not distinct, vertices such that the cycles  $uv_1v_k$  and  $wv_lv_{l+1}$  are each faces of  $G$ .

Since  $G$  is weakly triangulated,  $G - C$  is nonempty, and  $C$  has no chords, it follows that  $G - C$  is connected. Thus there exists a  $uw$ -path in  $G - C$ . Let  $T$  be the shortest such path, and note that therefore  $T$  is an induced path. Color  $T$  with the remaining color not used on  $P$  or  $Q$ .

Let  $C_1$  be the cycle consisting of  $P$ ,  $T$ , and the edges  $v_1u$  and  $v_lw$ . Similarly, let  $C_2$  be the cycle consisting of  $T$ ,  $Q$ , and the edges  $v_ku$  and  $v_{l+1}w$ . Then we may apply the algorithm to path 3-color  $\text{Int}(C_1)$  and  $\text{Int}(C_2)$ . Since  $\text{Int}(C_1)$  and  $\text{Int}(C_2)$  have only the vertices of the path  $T$  in common, the combined coloring forms a path 3-coloring of  $G$ .

Given any plane graph  $G$  we may add edges until it is triangulated. Observe that any path coloring of  $G$  with the additional edges is also a path coloring of the original  $G$ . Therefore by path 2-coloring the outer triangle we may apply Poh's algorithm to path 3-color  $G$ . This observation yields the following result.

**Theorem 4.1** (Poh [19] and Goddard [14]). *All planar graphs are path 3-colorable.*

## The Poh Algorithm with Breadth First Search

In order to implement Poh's algorithm with adjacency lists there are two main obstacles. First, we must have a method to efficiently represent colored paths, as we will be recursively constructing paths and dividing the graph along them. Second, we will need an efficient algorithm to locate the chords of  $C$  and the  $uw$ -path.



Figure 4.2: Dividing  $G$  along the edge  $v_i v_j$  and the  $uw$ -path.

Let  $G$  be a 2-connected weakly triangulated plane graph with an adjacency list representation. Each call of the algorithm will be provided with a cycle  $C$  in  $G$  and produce a path 3-coloring of  $\text{Int}(C)$  according to the specifications of Poh's algorithm.

To represent induced paths in  $G$  we will simply use the color vertex property. Suppose  $P = v_1 v_2 \dots v_k$  is an induced path in  $G$  that has been colored with  $c_P$ . Assume the coloring constructed so far is a path coloring. If  $v_i \in P$  then a neighbor  $u$  of  $v_i$  will have the color  $c_P$  if and only if  $u \in P$ , that is,  $u = v_{i-1}$  or  $u = v_{i+1}$ . Therefore we may represent the entire path by storing just the vertices  $v_1$  and  $v_k$ .

We will now describe the first version of Poh's algorithm on adjacency list graphs, using a breadth first search to find induced paths and chords.

**Algorithm 4.2.** (Poh – BFS)

**Assumptions:** Suppose  $P = v_1 v_2 \dots v_l$  and  $Q = v_k v_{k-1} \dots v_{l+1}$  are induced paths such that  $C = v_1 v_2 \dots v_k$  is a cycle. Additionally, assume each path has been colored with a distinct color.

**Input:** The paths  $P$  and  $Q$ , each represented by their endpoints as described above.

**Output:** We find an extension of the 2-coloring of  $C$  to a path 3-coloring of  $\text{Int}(C)$  such that no vertex in  $C$  receives a same color neighbor in  $\text{Int}(C) - C$ .

**Description:** Locate the position of  $v_k$  in  $\text{Adj}[v_1]$ . Proceeding one vertex further in  $\text{Adj}[v_1]$  gives us a vertex  $u$  such that the cycle  $uv_1 v_k$  is a triangle.

*Case 1:* Suppose  $u \in C$ . If  $u$  is in  $P$ , i.e.  $u = v_2$ , we apply the algorithm to the paths  $P - u$  and  $Q$ . Similarly if  $w$  is in  $Q$  we apply the algorithm to  $P$  and  $Q - u$ . In either case, if the two remaining paths each consist of single vertex then there are no remaining uncolored vertices and we terminate the algorithm.

*Case 2:* Suppose  $u \notin C$ . Perform a breadth first search from  $u$  in  $\text{Int}(C) - C$ , that is, ignoring vertices in  $C$ . Terminate the search when we reach a vertex  $w$  with





Figure 4.3: The collection of graphs  $\{G_k\}_{k \in \mathbb{N}}$  on which Poh performs poorly.

neighbors  $v_i \in P$  and  $v_j \in Q$  such that  $v_i$  is immediately past  $v_j$  in  $\text{Adj}[w]$ . Such a vertex must exist by the same argument as in *Poh 3-Coloring* (4.1). Backtracking from  $w$  along the breadth first search and coloring vertices produces an induced  $uw$ -path  $T$ , colored with the remaining color not used on  $P$  or  $Q$ .

Define the paths  $P_1 = v_1 v_2 \dots v_i$ ,  $P_2 = v_i v_{i+1} \dots v_l$ ,  $Q_1 = v_k v_{k-1} \dots v_j$ , and  $Q_2 = v_j v_{j-1} \dots v_{l+1}$ . Observe we have a cycle  $C_1$  consisting of  $P_1$ ,  $T$ , and the edges  $v_1 u$  and  $v_i w$ . Similarly we have a cycle  $C_2$  consisting of  $T$ ,  $Q_1$ , and the edges  $v_k u$  and  $v_j w$ . We apply the algorithm to  $P_1$  and  $T$  to color  $\text{Int}(C_1)$  and similarly to  $T$  and  $Q_1$  to color  $\text{Int}(C_2)$ .

If  $i = l$  and  $j = l + 1$  we are done. Otherwise, we have the cycle  $C_3$  consisting of  $P_2$ ,  $Q_2$  and the edges  $v_i v_j$  and  $v_l v_{l+1}$ , and we may apply the algorithm to color  $\text{Int}(C_3)$ .

Note the combined coloring forms a path 3-coloring of  $\text{Int}(C)$  by the same argument as in *Poh 3-Coloring* (4.1).

**Complexity:** In the first step we rotate through  $\text{Adj}[v_1]$  to find  $v_k$  and get an orientation within the graph. This orientation must be performed at most once for each vertex, for a total of at most  $\sum_{v=0}^{n-1} \deg(v) = 2m$  operations.

In the next step we perform a breadth first search from the vertex  $u$ . A breadth first search requires at most  $m$  lookups. Moreover, the vertex  $u$  will be colored following the search. Thus we perform at most one breadth first search from each vertex, requiring at most  $nm$  operations. Therefore the complexity of the algorithm is  $\mathcal{O}(2m + nm) = \mathcal{O}(n^2)$ .

We define the collection of graphs  $\{G_k\}_{k \in \mathbb{N}}$ , depicted in Figure 4.3. Let us fix  $k \in \mathbb{N}$  and note  $G_k$  has  $n = \frac{k^2+k}{2} + 3$  vertices.

Suppose we apply *Poh BFS* (4.2) to path 3-color  $G_k$ . Let the initial 2-coloring of the outer triangle of  $G_k$  assign the top vertex a color distinct from the bottom two. The  $(k - i + 1)$ th recursive call will perform a breadth first search visiting each vertex in a subgraph of size  $\frac{i^2+i}{2}$ , hence requiring  $\Theta(\frac{i^2+i}{2})$  operations. The total number of

operations required to path 3-color  $G_k$  is therefore

$$\Theta\left(\sum_{i=1}^k \frac{i^2 + i}{2}\right) = \Theta(n^{3/2}).$$

Thus the time complexity of the algorithm is  $\Omega(n^{3/2})$ . In particular the algorithm is not linear.

## The Poh Algorithm in Linear Time

Poh's proof requests that we find the shortest  $uv$ -path in  $\text{Int}(C)$ . Therefore Poh's algorithm as written does not appear to admit a linear time algorithm.

However, the correctness of Poh's algorithm does not require that  $T$  be the shortest  $uv$ -path, only that  $T$  be an induced  $uv$ -path. We will show that Poh's algorithm is linear if we instead construct an induced  $uv$ -path consisting of vertices in  $G - C$  with at least one neighbor in the colored path  $P$ .

### Algorithm 4.3. (Poh – Path Walk)

**Assumptions:** Assume  $P = v_1v_2 \dots v_l$  and  $Q = v_kv_{k-1} \dots v_{l+1}$  are induced paths, each colored with a distinct color, such that  $C = v_1v_2 \dots v_kv_{k-1} \dots v_{l+1}$  is a cycle.

**Input:** The path  $P$ , represented by its endpoints, and the color of the path  $Q$ .

**Output:** We find an extension of the 2-coloring of  $C$  to a path 3-coloring of  $\text{Int}(C)$  such that no vertex in  $C$  receives a same color neighbor in  $\text{Int}(C) - C$ .

**Description:** We will iterate through the vertices of  $P$  until we find a chord. All interior vertices visited will be marked to indicate they have a neighbor in  $P$ . For each  $i$  from 1 to  $l$  let us walk through  $\text{Adj}[v_i]$  from  $v_{i-1}$  to  $v_{i+1}$ , not including  $v_{i-1}$  and  $v_{i+1}$ .

Let  $v$  be the current neighbor. If  $v = v_j \in Q$  then  $v_iv_j$  is a chord of  $C$  and we stop. Otherwise  $v \in \text{Int}(C) - C$  with the neighbor  $v_i \in P$  and we mark it.

Define the cycles  $C_1$  and  $C_2$  as usual by dividing  $C$  along the chord  $v_iv_j$ . Note  $C_1$  is chordless as  $P$  and  $Q$  are induced paths and  $v_iv_j$  is the first chord of  $C$  encountered. Apply *Path Walk* (4.3) to path 3-color  $\text{Int}(C_2)$ . It remains to color  $\text{Int}(C_1)$ .

If we never encountered a vertex in  $\text{Int}(C) - C$  during our walk through the neighbors of  $v_1, \dots, v_i$ , then  $\text{Int}(C_1) - C_1$  is empty and thus  $\text{Int}(C_1)$  is already colored. Otherwise let  $u$  be the first such neighbor encountered. Note  $u$  is the unique vertex such that  $uv_1v_i$  is a face. We may therefore apply *Path Trace* (4.4) to path 3-color  $\text{Int}(C_1)$ .

The combined coloring is a path 3-coloring of  $\text{Int}(C)$  by the same argument as in *Poh 3-Coloring* (4.1).

**Complexity:** See *Path Trace* (4.4).

**Algorithm 4.4.** (Poh – Path Trace)

**Assumptions:** Let  $P = v_1v_2 \dots v_l$  and  $Q = v_kv_{k-1} \dots v_{l+1}$  be induced paths, each colored with a distinct color, such that  $C = v_1v_2 \dots v_kv_k$  is a chordless cycle. In addition, suppose  $\text{Int}(C) - C$  is nonempty and all vertices in  $\text{Int}(C) - C$  with at least one neighbor in  $P$  have been marked.

**Input:** The vertex  $u \in \text{Int}(C) - C$  such that the cycle  $uv_1v_k$  is a face, as well as the respective colors of the paths  $P$  and  $Q$ .

**Output:** We find an extension of the 2-coloring of  $C$  to a path 3-coloring of  $\text{Int}(C)$  such that no vertex in  $C$  receives a same color vertex in  $\text{Int}(C) - C$ .

**Description:** Initialize  $T$  as the path consisting of the single vertex  $u$ , coloring  $u$  with the remaining color. We will recursively add vertices to  $T$  until we reach the unique vertex  $w$  such that  $wv_lv_{l+1}$  is a face.

Suppose we have constructed the induced path  $T = t_1t_2 \dots t_d$ , such that  $t_1 = u$  and each  $t_i$  has at least one neighbor in  $P$ . Iterate through  $\text{Adj}[t_d]$ , starting from  $t_{d-1}$ . Let  $v$  be the current neighbor. If  $v$  has a neighbor in  $P$  we color  $v$ , assign  $T = t_1 \dots t_dv$ , and repeat the process with  $v$  as the new end vertex. If  $v \in P$  it must be that  $t_d = w$  and we are finished constructing  $T$ . Otherwise ignore  $v$  and move to the next neighbor.

Note the process above must terminate since each vertex in  $T$  has at least one neighbor in  $P$ .

Let  $T = t_1t_2 \dots t_d$  be the path constructed above. Suppose  $t_it_j$  is an edge with  $t_i, t_j \in T$ ,  $i < j$ . If  $i = 1$  let us define the vertex  $t_0$  to be  $v_1$ . Since each vertex in  $T$  has a neighbor in  $P$ , by planarity it must be that  $t_j$  is between  $t_{i-1}$  and  $t_{i+1}$  counterclockwise in  $\text{Adj}[t_i]$ . But by the construction of  $T$ ,  $t_{i+1}$  is the first neighbor of  $t_i$  counterclockwise from  $t_{i-1}$ . Thus  $j = i + 1$ .

Therefore the only edges between vertices in  $T$  are the edges  $t_1t_2, \dots, t_{d-1}t_d$ . So  $T$  is an induced path.

We apply *Path Walk* (4.3) to path 3-color  $\text{Int}(C_2)$ . It remains to color any uncolored vertices in  $\text{Int}(C_1)$ .

All vertices in  $T$  have at least one neighbor in  $P$ . Therefore any uncolored vertex in  $\text{Int}(C_1)$  must lie in a path 2-colored chordless cycle of the form  $v_iv_{i+1} \dots v_jt_{p+1}t_p$  or  $v_iv_{i+1} \dots v_jt_p$ . We will use the following procedure to locate all such cycles that contain uncolored vertices and color them using *Path Trace* (4.4).

For each  $p$  from 1 to  $d$  let us iterate through  $\text{Adj}[t_p]$ , starting with  $t_{p+1}$ . In the case  $p = d$  we will define  $t_{p+1} = v_l$ . Suppose we visit a neighbor  $y \in \text{Int}(C_1) - C_1$  followed counterclockwise by a neighbor  $v_i \in P$ . There are two possible cases.

*Case 1:* Suppose none of the neighbors of  $t_p$  between  $t_{p+1}$  and  $v_i$  counterclockwise are in  $P$ . Let  $j$  be the smallest integer such that  $t_{p+1}v_j$  is an edge, noting again that  $i < j$  by planarity. Note since  $P$  is an induced path the cycle  $C_y = t_pv_iv_{i+1} \dots v_jt_{p+1}$  is chordless by the our selection of  $v_j$ . Thus we may apply *Path Trace* (4.4) to color  $\text{Int}(C_y)$  with the vertex  $y$  forming the face  $yt_pv_i$ .

*Case 2:* Suppose we have previously visited a neighbor of  $t_p$  in  $P$ , and let  $v_j \in P$

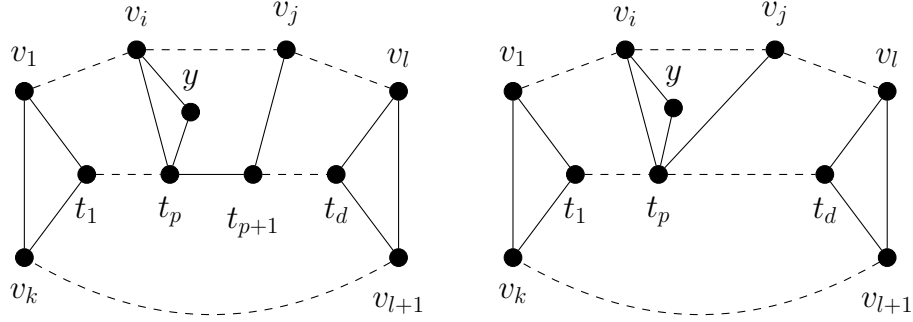


Figure 4.4: Coloring vertices above  $T$  in *Path Trace* (4.4) case 1 (left), case 2 (right).

be the most recent such neighbor visited. Note by planarity it must be that  $i < j$ . Note the cycle  $C_y = v_i v_{i+1} \dots v_j t_p$  is chordless since  $P$  is an induced path. We may therefore apply *Path Trace* (4.4) to color  $\text{Int}(C_y)$  with the vertex  $y$  forming the face  $y t_p v_i$ .

**Complexity:** Let  $G$  be a plane graph that has been colored with Poh. Let  $P$  be a path induced by the path 3-coloring of  $G$ . Note each vertex is in exactly one such path.

Let  $v \in P$ . We iterated through  $\text{Adj}[v]$  exactly once during *Path Walk* (4.3). We iterated through  $\text{Adj}[v]$  at most twice during *Path Trace* (4.4): once to locate the starting neighbor, and once to find the next vertex to add to the path and find uncolored vertices above  $T$ .

Thus the time complexity of the algorithm is

$$\mathcal{O}\left(\sum_{v=0}^{n-1} 3 \cdot \deg(v)\right) = \mathcal{O}(6m) = \mathcal{O}(n).$$

More specifically, it is  $\Theta(n)$ .

## 5 Path List-Coloring and the Hartman-Skrekovski Algorithm

In this section we describe an algorithm for path list-coloring plane graphs with lists of size 3. The following algorithm on abstract graphs is due to the independent work of Hartman [17] and Skrekovski [22].

Note that the description of the algorithm given below is structured differently than the descriptions given by both Hartman and Skrekovski. This restructuring is, in many ways, less elegant than both original proofs, but helps illuminate how the

algorithm will operate on a graph with an adjacency list representation.

**Algorithm 5.1.** (Hartman-Skrekovski – Path Color)

**Input:** Let  $G$  be a 2-connected weakly triangulated plane graph with outer cycle  $C = v_1v_2 \dots v_k$ . Let  $x = v_1$  and  $y \in C - x$ . Suppose  $L$  is a list assignment for  $G$  such that for each vertex  $v \in G$

$$\begin{aligned} |L(v)| &\geq 1 && \text{if } v = x \text{ or } v = y; \\ |L(v)| &\geq 2 && \text{if } v \in C - x - y; \\ |L(v)| &\geq 3 && \text{otherwise.} \end{aligned}$$

We will call  $x$  and  $y$  the *fixed* vertices. Assume all vertices are uncolored except for potentially  $x$  and  $y$ . If  $x$  or  $y$  are colored assume  $L(x)$ ,  $L(y)$  contain only the color they have been assigned.

**Output:** A path  $L$ -list-coloring of  $G$  such that the fixed vertices  $x$  and  $y$  each receive at most one same color neighbor.

**Description:** If  $x$  is already colored let  $c$  be the color of  $x$ . Otherwise select arbitrary  $c \in L(x)$ . We will construct an induced path  $P$ , colored with  $c$ , and consisting of vertices from  $C$ . The path will begin at  $x$  and proceed clockwise along the outer face a far as possible towards  $y$ . Initialize  $P$  to consist of the single vertex  $x$ .

Suppose we have constructed an induced path  $P = v_{j_1}v_{j_2} \dots v_{j_l}$  with  $1 = j_1 < j_2 < \dots < j_l < k$ . Let us select the largest integer  $i$  such that  $v_i \in C[v_{j_l}, y]$  and  $c \in L(v_i)$ . If no such  $i$  exists we have finished constructing  $P$ . Otherwise we append  $v_i$  to  $P$  and repeat.

Let  $L'$  be a list assignment for  $G$  defined such that for  $v \in G$

$$L'(v) = \begin{cases} \{c\}, & \text{if } v \in P; \\ L(v), & \text{otherwise.} \end{cases}$$

Let  $P = v_{j_1}v_{j_2} \dots v_{j_l}$  be the path constructed above. For each vertex in  $v_{j_i} \in P$ , color  $v_i$  with  $c$ .

Suppose  $i \in \{1, \dots, l-1\}$  such that  $j_i + 1 < j_{i+1}$ . We apply *Remove Path* (5.2) to path  $L'$ -list-color the subgraph bounded by the cycle consisting of  $C[v_{j_i}, v_{j_{i+1}}]$  and the edge  $v_{j_i}v_{j_{i+1}}$ , with colored path  $v_{j_{i+1}}v_{j_i}$ , and fixed vertices  $v_{j_{i+1}}$  and  $v_{j_{i+1}-1}$ .

If  $y \in P$  let us define  $y' = v_{j_l+1}$ , otherwise  $y' = y$ . We may apply *Remove Path* (5.2) to path  $L'$ -list-color the subgraph bounded by the cycle consisting of  $P$  and  $C[v_{j_l}, v_{j_1}]$ , with colored path  $P$ , and fixed vertices  $v_k$  and  $y'$ .

Pairwise all subgraphs above have only vertices in the path  $P$  in common. By *Remove Path* (5.2), no vertex with a neighbor in  $P$  will receive the color  $c$ . Therefore the combined coloring is a path  $L$ -list-coloring of  $G$  such that  $x, y$  receive at most one same color neighbor.

**Algorithm 5.2.** (Hartman-Skrekovski – Remove Path)

**Input:** Let  $G$  be a 2-connected weakly triangulated plane graph with outer cycle  $C = v_1v_2 \dots v_k$ . Let  $P = v_1v_2 \dots v_l$  be an induced path in  $C$ . Let  $x = v_k$  and  $y \in C - P$ . Let  $L$  be a list assignment for  $G$  such that for  $v \in G$

$$\begin{aligned} L(v) &= \{c\} && \text{if } v \in P; \\ |L(v)| &\geq 1 && \text{if } v = x \text{ or } v = y; \\ |L(v)| &\geq 2 && \text{if } v \in C - P - x - y; \\ |L(v)| &\geq 3 && \text{otherwise.} \end{aligned}$$

Assume if  $|L(x)| = 1$  then  $c \notin L(x)$ . Additionally, assume for every  $v \in C[v_{l+1}, y]$ , if  $v$  has a neighbor in  $P$  then  $c \notin L(v)$ .

We will once again refer to  $x$  and  $y$  as fixed vertices, although in this algorithm it may be the case that  $x = y$ . Assume all vertices are uncolored except for potentially  $x$  and  $y$ . If  $x$  or  $y$  are colored assume  $L(x)$ ,  $L(y)$  contain only the color they have been assigned.

**Output:** A path  $L$ -list-coloring of  $G$  such that  $x$  and  $y$  each receive at most one same color neighbor, and no vertex in  $G - P$  with a neighbor in  $P$  receives the color  $c$ . If  $x = y$  then  $x$  will receive no same colored neighbors in  $G$ .

**Description:** Note  $G$  is 2-connected and weakly triangulated. Thus to disconnect  $G$  by removing vertices from  $C$  we would need to remove vertices  $v_i, v_j \in C$  such that  $v_iv_j$  is a chord of  $C$ . Observe  $P$  is a subgraph of  $C$  and an induced path in  $G$ , so no vertices in  $P$  induce a chord of  $C$ . So  $G - P$  is connected.

*Case 1:* Suppose there is a chord of  $C$  with an endpoint in  $P$ . Let us select the smallest  $i \in \{1, \dots, l\}$  and largest  $j \in \{l+2, \dots, k-1\}$  such that  $v_i \in P$  and  $v_iv_j$  is a chord of  $C$ . Let  $C_1$  be the cycle consisting of  $C[v_j, v_i]$  and the edge  $v_iv_j$ . Similarly, let  $C_2$  be the cycle consisting of  $C[v_i, v_j]$  and the edge  $v_iv_j$ . Let  $P_1 = v_1v_2 \dots v_i$  and  $P_2 = v_iv_{i+1} \dots v_l$ .

*Case 1.1:* Suppose  $y \in C[v_{l+2}, x]$  and  $v_j \in C[v_{l+2}, y]$ . Then  $x, y \in C_1$ . We will first apply *Remove Path* (5.2) to path  $L$ -list-color  $\text{Int}(C_1)$  with the colored path  $P_1$ , and fixed vertices  $x$  and  $y$ . We then apply *Remove Path* (5.2) to path  $L$ -list-color  $\text{Int}(C_2)$  with colored path  $P_2$ , and the single fixed vertex  $v_j$ .

The subgraphs  $\text{Int}(C_1)$  and  $\text{Int}(C_2)$  have only the chord  $v_iv_j$  in common. The vertex  $v_i$  is an endpoint of the colored path in both  $\text{Int}(C_1)$  and  $\text{Int}(C_2)$ . Thus  $v_i$  will receive at most one same color neighbor in each. Since  $v_j$  is the single fixed vertex in  $\text{Int}(C_2)$ ,  $v_j$  will receive no same color neighbors in  $\text{Int}(C_2)$ . Thus the combined coloring is a path  $L$ -list-coloring of  $G$  with  $x, y$  receiving the correct number of shared color neighbors.

*Case 1.2:* Otherwise  $v_j \in C[y, v_{k-1}]$ ,  $v_j \neq y$ . Again, we first apply *Remove Path* (5.2) to path  $L$ -list-color  $\text{Int}(C_1)$  with the colored path  $P_1$ , and fixed vertices  $x$  and  $v_j$ . We may then apply *Remove Path* (5.2) to path  $L$ -list-color  $\text{Int}(C_2)$  with colored path  $P_2$ , and fixed vertices  $v_j$  and  $y$ .

Again  $\text{Int}(C_1)$  and  $\text{Int}(C_2)$  have only the chord  $v_iv_j$  in common. In both  $\text{Int}(C_1)$  and  $\text{Int}(C_2)$  the vertex  $v_j$  is fixed vertex, and  $v_i$  is an endpoint of the colored path.

Therefore  $v_i$  and  $v_j$  will both have at most one same color neighbor in each subgraph. Thus the combined coloring is a path  $L$ -list-coloring of  $G$  with  $x, y$  receiving the correct number of shared color neighbors.

*Case 2:* Suppose there are no chords of  $C$  with endpoints in  $P$ . Let  $L'$  be a list assignment for  $G - P$  defined by

$$L'(v) = \begin{cases} L(v) \setminus \{c\}, & \text{if } v \text{ has at least one neighbor in } P; \\ L(v), & \text{otherwise.} \end{cases}$$

*Case 2.1:* Suppose  $G - P$  is 2-connected. Let  $v \in G - P$ .

Suppose  $v$  is not on the outer face of  $G - P$ . Then  $v$  has no neighbors in  $P$  and  $|L'(v)| = |L(v)| \geq 3$ .

Suppose  $v$  is on the outer face of  $G - P$ ,  $v \notin C$ . Then  $v$  has at least one neighbor in  $P$  and  $|L'(v)| \geq |L(v)| - 1 \geq 2$ .

Finally, suppose  $v \in C$ . Since there are no chords of  $C$  with endpoints in  $P$  the only vertices in  $C - P$  with neighbors in  $P$  are  $x$  and  $v_{l+1}$ . Recall we assumed that if  $v \in C[v_{l+1}, y]$  and  $v$  has at least one neighbor in  $P$  then  $c \notin L(v)$ . Thus if  $v \neq x$ ,  $v \neq y$ , then  $|L'(v)| = |L(v)| \geq 2$ . We ensured  $c \notin L(x)$  if  $|L(x)| = 1$ . Thus if  $v = x$  or  $v = y$ ,  $|L'(v)| \geq 1$ .

Therefore  $L'$  meets the requirements of *Path Color* (5.1) with fixed vertices  $x$  and  $y$ . Moreover, by the definition of  $L'$ , in a path  $L'$ -list-coloring of  $G - P$  no vertex with a neighbor in  $P$  will receive the color  $c$ .

*Case 2.1.1:* Suppose  $x \neq y$ . Then we may apply *Path Color* (5.1) to path  $L'$ -list-color  $G - P$  with fixed vertices  $x$  and  $y$ , the new path starting at  $x$ .

*Case 2.1.2:* Suppose  $x = y$ . If  $x$  is uncolored select arbitrary  $c_x \in L'(x)$ , color  $x$  with  $c_x$ , and define  $L'(x) = \{c_x\}$ . Apply *Remove Path* (5.2) to path  $L'$ -list-color  $G - P$  with the colored path consisting of the single vertex  $x$ , and the vertices adjacent to  $x$  on the outer cycle of  $G - P$  as fixed vertices. This ensures  $x$  receives no same colored neighbors in  $G$ .

*Case 2.2:* Finally, if  $G - P$  is not 2-connected, then  $G - P$  must be a complete graph on one or two vertices. It is simple to check we may  $L'$ -list-color  $G - P$  such that the requirements hold.

Let  $G$  be a plane graph and  $L$  a list assignment such that  $|L(v)| \geq 3$  for all  $v \in G$ . We may add edges to  $G$  until it is triangulated. Then we may apply *Path Color* (5.1), with arbitrary fixed vertices, to construct a path  $L$ -list-coloring. This yields the following result.

**Theorem 5.1** (Hartman [17]). *All planar graphs are path 3-choosable.*

## The Hartman-Skrekovski Algorithm with Adjacency Lists

In order to implement Hartman and Skrekovski's algorithm with adjacency lists there are two main challenges. First, we need to be able to remove paths and locate

the subgraphs for recursive calls. Second, we must be able to track the location of vertices on the outer face with respect to the fixed vertices  $x$ , and  $y$ . For example: when adding a vertex to the path  $P = v_{j_1}v_{j_2} \dots v_{j_l}$  in *Path Color* (5.1), we need to know which neighbors of  $v_{j_l}$  lie in  $C[v_{j_l}, y]$ .

For now, let us assume we have solved the second challenge described above. That is, given vertices  $u, v, w \in C$ , assume we can determine whether  $v \in C[u, w]$  in  $\mathcal{O}(1)$  time.

Let  $G$  be a 2-connected weakly triangulated plane graph with an augmented adjacency list representation. Just as in Poh's algorithm, each call will be provided with a cycle  $C = v_1v_2 \dots v_k$  in  $G$ . The job of a particular recursive call is then to color the subgraph  $\text{Int}(C)$  such that the requirements of the Hartman-Skrekovski algorithm hold.

We will provide each vertex in  $G$  with a boolean vertex property to represent its state. All vertices in  $C$  will have a state indicating they are on the outer face, and likewise vertices in  $\text{Int}(C) - C$  will have a state indicating they are not in  $C$ .

The list assignment  $L$  will be represented by vertex property storing a linked list of colors  $L[v]$  for each  $v \in G$ . We will denote the number of colors in the linked list by  $|L[v]|$ . We will produce a coloring of  $G$  by reducing the size of each color list to one. Thus we consider a vertex  $v$  colored if  $|L[v]| = 1$ .

For each vertex  $v_i \in C$  we will store a vertex property  $\text{Nbr}[v_i]$  called a *neighbor range*. The neighbor range of  $v_i$  will contain a pair of references to nodes in  $\text{Adj}[v_i]$ , that is  $\text{Nbr}[v_i] = (r_1, r_2)$ . The first reference  $r_1$  will point to the node for  $v_{i-1}$  in  $\text{Adj}[v_i]$  and the reference  $r_2$  will point to the node for  $v_{i+1}$ .

Neighbor ranges provide immediate access to the preceding and subsequent vertices of  $v_i$  in  $C$ . Additionally, they give start and stop nodes in  $\text{Adj}[v_i]$  for the list of neighbors of  $v_i$  that are contained in the subgraph  $\text{Int}(C)$ .

**Algorithm 5.3.** (Hartman-Skrekovski – Path Color)

**Assumptions:** Suppose  $C = v_1v_2 \dots v_k$  is a cycle,  $x = v_1$ , and  $y \in C - x$ . Assume for each  $v \in \text{Int}(C)$

$$\begin{aligned} |L[v]| &\geq 1 && \text{if } v = x \text{ or } v = y; \\ |L[v]| &\geq 2 && \text{if } v \in C - x - y; \\ |L[v]| &\geq 3 && \text{otherwise.} \end{aligned}$$

Assume the vertices of  $\text{Int}(C)$  have been assigned according to whether they are in  $C$  or  $\text{Int}(C) - C$ . Finally, assume for each  $v_i \in C$  we have constructed  $\text{Nbr}[v_i]$  as described above.

**Input:** The fixed vertices  $x$  and  $y$ .

**Output:** A path  $L$ -list-coloring of  $\text{Int}(C)$  such that  $x$  and  $y$  each receive at most one same color neighbor.

**Description:** If  $x$  is colored let  $c$  be the color of  $x$ . Otherwise let  $c$  be the first color in  $L[x]$  and assign  $L[x] = \{c\}$ .



Initialize  $P$  to contain the single vertex  $x$ . We will now append vertices to  $P$  following the procedure of *Path Color* (5.1).

Suppose we have constructed an induced path  $P = v_{j_1}v_{j_2}\dots v_{j_l}$  with  $1 = j_1 < j_2 < \dots < j_l < k$ . Let  $v = v_{j_l}$  be the last vertex added to  $P$ . Let us iterate through  $\text{Adj}[v]$  counterclockwise from  $v_{j_{l-1}}$ , if  $l = 1$  start from  $v_k$ . Let  $u$  be the current neighbor.

*Case 1:* If  $u \notin C[v, y]$  or  $c \notin L(u)$  then we ignore  $u$  and continue to the next vertex in  $\text{Adj}[v]$ .

*Case 2:* Suppose  $u = v_i \in C$ ,  $u \in C[v, y]$ , and  $c \in L(u)$ , that is, suppose we may add  $u$  to  $P$ . There are two cases to consider.

*Case 2.1:* Suppose the start node of  $\text{Nbr}[u]$  is not  $v$ . Then  $u \neq v_{j_{l+1}}$ . Let  $\text{Nbr}[u] = (r_1, r_2)$  and  $\text{Nbr}[v_{j_l}] = (s_1, s_2)$ . Let  $r_v$  be the reference to the node for  $v$  in  $\text{Adj}[u]$  and  $s_u$  be the reference to the node for  $u$  in  $\text{Adj}[v]$ .

Let us assign  $\text{Nbr}[u] = (r_1, r_v)$  and  $\text{Nbr}[v] = (s_u, s_2)$ . We will then call *Remove Path* (5.4) on the cycle consisting of  $C[v, u]$  and the edge  $uv$ , with colored path  $uv$ , and fixed vertices  $v_{i-1}$  and  $y = v_{j_{l+1}}$ .

We then assign  $\text{Nbr}[u] = (r_v, r_2)$  and  $\text{Nbr}[v] = (s_1, s_u)$ . Finally, color  $u$  with  $c$ , assign  $L[u] = \{c\}$ , append  $u$  to  $P$ , and attempt to continue the path from  $u$ .

*Case 2.2:* Suppose the start node of  $\text{Nbr}[u]$  is  $v$ . Then we may color  $u$  with  $c$ , assign  $L[u] = \{c\}$ , append  $u$  to  $P$ , and attempt to continue the path from  $u$ .

Let  $P = v_{j_1}v_{j_2}\dots v_{j_l}$  be the path constructed above. If  $y \in P$  let us define  $y' = v_{j_{l+1}}$ , otherwise  $y' = y$ . We may finally apply *Remove Path* (5.4) to the cycle formed by  $P$  and  $C[v_{j_l}, v_{j_1}]$ , with colored path  $P$ , and fixed vertices  $v_k$  and  $y'$ .

**Complexity:** See *Remove Path* (5.4).

#### Algorithm 5.4. (Hartman-Skrekovski – Remove Path)

**Assumptions:** Suppose  $C = v_1v_2\dots v_k$  is a cycle. Let  $P = v_1v_2\dots v_l$  be an induced path in  $C$  colored with some color  $c$ . Let  $y \in C - P$  and  $x \in C[y, v_k]$ . Let  $L$  be a list assignment for  $G$  such that for each  $v \in G$

$$\begin{aligned} L[v] &= \{c\} && \text{if } v \in P; \\ |L[v]| &\geq 1 && \text{if } v = x \text{ or } v = y; \\ |L[v]| &\geq 2 && \text{if } v \in C - P - x - y; \\ |L[v]| &\geq 3 && \text{otherwise.} \end{aligned}$$

Assume for every  $v \in C[x, v_k]$ ,  $c \notin L(v)$ . Additionally, assume for every  $v \in C[v_{l+1}, y]$ , if  $v$  has a neighbor in  $P$  then  $c \notin L(v)$ .

**Input:** The vertices  $v_1$ ,  $x$ , and  $y$ .

**Output:** A path  $L$ -list-coloring of  $G$  such that  $x$  and  $y$  each receive at most one same color neighbor, and no vertex in  $G - P$  with a neighbor in  $P$  receives the color  $c$ . If  $x = y$  then  $x$  will receive no same colored neighbors in  $G$ .

**Description:** We will remove the path  $P$  one vertex at a time. In this call we will be “removing” edges around  $v_1$ , by updating  $\text{Nbr}[v]$  to exclude them. We will completely removing  $v_1$  from  $\text{Int}(C)$  if there are no chords  $v_1v_i$  of  $C$ .



Figure 5.1: From left to right: case 2.2.1, case 2.2.2, and case 2.2.3.

Let us iterate counterclockwise through  $\text{Adj}[v_1]$  beginning from  $v_k$ . Let  $u$  be the current neighbor of  $v_1$ .

*Case 1:* Suppose  $u \notin C$ . Look through  $L[u]$  and remove the color  $c$  if it exists. After removing  $v_1$ ,  $u$  will be on the outer face. Thus we set the state of  $u$  to indicate it is on the outer face. Construct  $\text{Nbr}[u] = (r_1, r_2)$  such that  $r_1$  is a reference to the node immediately prior to  $v_1$  in  $\text{Adj}[u]$  and  $r_2$  is a reference to the node immediately subsequent to  $v_1$ .

*Case 2:* Suppose  $u \in C$ . There are several cases to consider.

*Case 2.1:* Suppose  $u = v_k$ . Let  $\text{Nbr}[u] = (r_1, r_2)$ . By our assumptions  $r_2$  is a reference to the node for  $v_1$  in  $\text{Adj}[u]$ . Reassign  $r_2$  to be a reference to the node immediately prior to  $v_1$  in  $\text{Adj}[u]$ . This removes  $v_1$  from the set of neighbors of  $u$  contained in the cycle.

*Case 2.2:* Suppose  $u \neq v_k$ . In this case the edge  $v_1u$  is either a chord of  $C$  or  $u = v_2$ . Let  $N$  be the  $v_ku$ -path consisting of the neighbors of  $v_1$ . Let  $C_1$  be the cycle consisting of  $N$  and  $C[u, v_k]$ . If  $u \neq v_2$  let  $C_2$  be the cycle consisting of  $C[v_1, u]$  and the edge  $v_1u$ .

Let  $\text{Nbr}[u] = (r_1, r_2)$  and  $\text{Nbr}[v] = (s_1, s_2)$ . Let  $r_v$  be the reference to the node for  $v$  in  $\text{Adj}[u]$  and  $s_u$  be the reference to the node for  $u$  in  $\text{Adj}[v]$ .

In all cases below, before we apply an algorithm to color  $\text{Int}(C_1)$  we will assign  $\text{Nbr}[u] = (r_v, r_2)$  and  $\text{Nbr}[v] = (s_1, s_v)$ . Similarly, before applying an algorithm to color  $\text{Int}(C_2)$  we will assign  $\text{Nbr}[u] = (r_1, r_v)$  and  $\text{Nbr}[v] = (s_u, s_2)$ .

We will now path  $L$ -list-color  $\text{Int}(C_1)$  and, if  $u \neq v_2$ ,  $\text{Int}(C_2)$ . There are several cases to consider.

*Case 2.2.1:* Suppose  $u \in C[x, v_1]$ . Note in this case it must be that  $u \neq v_2$ . We will first apply *Remove Path* (5.4) to path  $L$ -list-color  $\text{Int}(C_2)$  with fixed vertices  $x$  and  $y$ . Note this colors the vertex  $u$ . We will apply *Remove Path* (5.4) with colored path consisting of just the vertex  $u$ , and the vertices immediately adjacent to  $u$  on  $C_1$  as the fixed vertices. This ensures  $u$  receives no same color neighbors in  $\text{Int}(C_1)$ .

*Case 2.2.2:* Suppose  $u \in C[y, x]$ ,  $u \neq y$ . Again it must be that  $u \neq v_2$ . We apply

*Color Path* (5.3) to path  $L$ -list-color  $\text{Int}(C_1)$  with fixed vertices  $x$  and  $u$ , the new path starting at  $x$ . Next we apply *Remove Path* (5.4) to  $\text{Int}(C_2)$  with fixed vertices  $u$  and  $y$ .

*Case 2.2.3:* Suppose  $u \in C[v_1, y]$ ,  $u \neq v_2$ . We apply *Color Path* (5.3) to path  $L$ -list-color  $\text{Int}(C_1)$  with fixed vertices  $x$  and  $y$ , the new path starting at  $x$ . We then apply *Remove Path* (5.4) to path  $L$ -list-color  $\text{Int}(C_2)$  with the single fixed vertex  $u$ . This ensures  $u$  receives no same color neighbors in  $\text{Int}(C_2)$ .

*Case 2.2.4:* Suppose  $u = v_2$ . If  $c \in L[u]$  then  $u$  is a path vertex and we apply *Remove Path* (5.4) to path  $L$ -list-color  $\text{Int}(C_1)$  with fixed vertices  $x$  and  $y$ . Otherwise, we have reached the end of the path. We apply *Color Path* (5.3) to  $\text{Int}(C_1)$  with fixed vertices  $x$  and  $y$ , the new path starting from  $x$ .

**Complexity:** Let  $v \in G$ . We iterate through  $\text{Adj}[v]$  at most once during *Color Path* (5.3) when looking for the next vertex to add to the path containing  $v$ . In *Remove Path* (5.4) we iterate through  $\text{Adj}[v]$  exactly once. We also iterate through  $\text{Adj}[v]$  once when we initially construct  $Nbr[v]$  to locate start and stop nodes. Therefore the overall complexity of the algorithm is

$$\mathcal{O}\left(\sum_{v=0}^{n-1} 3 \cdot \deg(v)\right) = \mathcal{O}(6m) = \mathcal{O}(n).$$

More specifically, it is  $\Theta(n)$ .

## Tracking Vertices on the Outer Cycle

The Hartman-Skrekovski algorithm described in the previous section relied on the assumption that we could immediately know the relative location of vertices on the outer cycle. In *Path Color* (5.3) we assumed we could determine whether a given vertex  $u \in C$  was in the path  $C[v, y]$ , where  $v$  was the last vertex added to our colored path. Additionally, in *Remove Path* (5.4) we assumed for  $u \in C$  we could determine whether  $u$  was in  $C[x, v_i]$ ,  $C[y, x]$ , or  $C[v_1, y]$ . We will now describe how this check may be accomplished in  $\mathcal{O}(1)$  time.

Let us define an integer vertex property to store a location mark for each vertex on the outer cycle. Assume we are given the input for *Remove Path* (5.4). Also assume vertices in  $C[v_1, y]$  have been assigned the mark  $n_1$ , vertices in  $C[y, x]$  have the mark  $n_2$ , and vertices in  $C[y, v_k]$  have the mark  $n_3$ .

Let us iterate through  $\text{Adj}[v_1]$  starting from  $v_k$  as in (5.4). Let  $u$  be the current neighbor. If  $u \notin C$  we will assign  $u$  the mark  $n_1$ . This is because  $u$  will be in  $C_1[x, v_2]$  if there are no chords  $v_1v_i$ .

Now suppose we reach the end of the colored path, or we hit a chord  $v_1u$  with  $u \in C[v_1, x]$ . Then in the subsequent call to *Color Path* (5.3) on  $\text{Int}(C_1)$  we will need to treat vertices marked  $n_1$  and  $n_2$  as the same segment, since  $C_1[x, y]$  consists of both  $C_1[x, v_k]$  and  $C_1[u, y]$ . One solution is to walk along  $C_1$  and remark vertices,

but this is very inefficient. Another solution is to simply compare with both marks to check whether a vertex is in  $C_1[x, y]$ . However, we will be drawing further colored paths and generating further marks, hence the collection of marks to compare may grow very large.

Our solution is to use a disjoint set structure to compare location marks. All marks begin as singleton sets. To join the segments marked with  $n_1$  and  $n_2$  above we may simply perform a union operation in the disjoint set structure.

The mark  $n_1$  for the segment  $C_1[x, v_k]$  will always be a singleton set in the disjoint set structure. This is because the only vertices marked with  $n_1$  are vertices that have been added to the outer face while removing vertices from the colored path. Thus in each union operation performed at least one of the two sets is always a singleton. Because of this, standard disjoint set optimizations allow set lookups in constant time. Therefore performing  $\mathcal{O}(n)$  make set, union, and lookup operations in the disjoint set structure requires  $\mathcal{O}(n)$  time. Hence the overall performance of the algorithm remains linear.

For full details on managing location marks and disjoint set operations, see the provided C++ implementation.

## 6 Path Coloring in C++ with the Boost Graph Library

The Boost Graph Library (BGL) [21] details a generic interface for working with graphs, as well as numerous data structures and algorithms for working with graphs. We will begin with a brief introduction to the BGL. Then we will discuss implementing the Poh and Hartman-Skrekovski algorithms using BGL abstractions.

We will assume familiarity with the C++ language and the C++ Standard Template Library (STL). Full hyperlinked documentation is available with the project source code at [https://github.com/permutationlock/path\\_coloring\\_bgl](https://github.com/permutationlock/path_coloring_bgl), with links to the relevant Boost and STL concepts.

### The Boost Graph Library

The BGL provides several abstract concepts for graph data structures. The basic `Graph` concept requires that a vertex and edge type to be defined, as well as a few properties such as whether the graph is directed or undirected. The `VertexListGraph` and `EdgeListGraph` refine this concept to additionally require an interface to iterate over the vertex and edge sets, respectively. The `VertexAndEdgeListGraph` concept simply combines the two refinements.

Although other concepts exist such as `AdjacencyGraph`, we will only require that input graphs model `VertexListGraph` or `VertexAndEdgeListGraph`. Although `AdjacencyGraph` might seem like an obvious choice, we will follow the BGL's deci-

```

template<
    typename graph_t ,
    typename planar_embedding_t ,
    typename color_map_t ,
    typename mark_map_t ,
    typename parent_map_t ,
    typename vertex_iterator_t ,
    typename color_t
>
void poh_color_bfs(
    const graph_t & graph ,
    const planar_embedding_t & planar_embedding ,
    color_map_t & color_map ,
    mark_map_t & mark_map ,
    parent_map_t & parent_map ,
    vertex_iterator_t p_begin , vertex_iterator_t p_end ,
    vertex_iterator_t q_begin , vertex_iterator_t q_end ,
    color_t c_0 , color_t c_1 , color_t c_2
);

```

Figure 6.1: Publicly visible function prototype for Poh with BFS.

sion and represent the rotation scheme for planar embeddings as an exterior property map.

There are two different types of vertex and edge properties in the BGL: interior properties and exterior properties. Interior properties are properties that are stored within the graph data structure. They are accessed or assigned via **get** or **put** functions, respectively, on the graph structure itself. Exterior properties are properties stored in a separate data structure. Calls to **get** and/or **put** on the property map structure then allow reads and/or writes to individual vertex or edge properties.

All our properties will be stored in exterior property maps that satisfy the **LvaluePropertyMap** concept. The **LvaluePropertyMap** concept requires that **get** calls on the property map return values by reference. The BGL defines the **PlanarEmbedding** concept to refine **LvaluePropertyMap** to require that each vertex is assigned a range of edges, representing the embedding ordered rotation scheme.

## Poh with BFS in the BGL

Here we describe our BGL implementation of *Poh – BFS* (4.2). The function prototype, type definitions, and template requirements are shown in figures 6.1, 6.2, and 6.3 respectively.

We assume the provided graph is simple and weakly triangulated and the given

Type	
<code>vertex_t</code>	<code>boost::graph_traits&lt;graph_t&gt;::vertex_descriptor</code>

Figure 6.2: Typedefinitions for Poh with BFS.

Type	Concept	Additional Requirements
<code>graph_t</code>	<code>VertexAndEdgeListGraph</code>	None
<code>color_t</code>	<code>EqualityComparable</code> , <code>CopyAssignable</code>	None
<code>embedding_t</code>	<code>PlanarEmbedding</code>	None
<code>color_map_t</code>	<code>LvaluePropertyMap</code>	<code>value_type</code> is <code>color_t</code>
<code>mark_map_t</code>	<code>LvaluePropertyMap</code>	<code>value_type</code> is an integer
<code>parent_map_t</code>	<code>LvaluePropertyMap</code>	<code>value_type</code> is <code>vertex_t</code>
<code>vertex_iterator_t</code>	<code>InputIterator</code>	<code>value_type</code> is <code>vertex_t</code>

Figure 6.3: Template requirements for Poh with BFS.

planar embedding structure represents a valid planar embedding of the graph. Finally we assume the two ranges of vertices map are paths in the graph satisfying the requirements of *Poh – BFS* (4.2). We assume no vertex is already colored any of `c_0`, `c_1`, or `c_2`. We also require that all vertices are initially assigned a mark of 0 by `mark_map`.

The implementation almost directly follows the description of (4.2), although some decisions had to be made. In order to keep the algorithm linear, we must ensure we iterate through the adjacency list of a given vertex precisely once during the orientation phase of (4.2). This is the step where we would locate the position of  $v_k$  in  $\text{Adj}[v_1]$ . To do this we note that at least one of the path endpoint vertices  $v_1$  or  $v_k$  has never been an path endpoint vertex in any call before. We then always choose this endpoint as the vertex whose adjacency list we search through.

Source code is available online at the link provided earlier.

## Poh with Path Walking in the BGL

Here we describe our BGL implementation of the linear time Poh algorithm described in (4.3) and (4.4). The function prototype, type definitions, and template requirements are shown in figures 6.4, 6.5, and 6.6 respectively.

We make the exact same assumptions about input structures as in our implementation of *Poh – BFS* (4.2) in the previous section.

The implementation follows algorithms (4.3) and (4.4) with the following implementation decisions and modifications. We use the `neighbor_range_map` structure to track start and stop points in the cyclic ordering of neighbors provided by

```

template<
    typename graph_t ,
    typename embedding_t ,
    typename color_map_t ,
    typename mark_map_t ,
    typename n_range_map_t ,
    typename vertex_iterator_t ,
    typename color_t
>
void poh_color(
    const graph_t & graph ,
    const embedding_t & planar_embedding ,
    color_map_t & color_map ,
    n_range_map_t & neighbor_range_map ,
    mark_map_t & mark_map ,
    vertex_iterator_t p_begin , vertex_iterator_t p_end ,
    vertex_iterator_t q_begin , vertex_iterator_t q_end ,
    color_t c_0 , color_t c_1 , color_t c_2
);

```

Figure 6.4: Publicly visible function prototype for Poh with Path Walking.

Type	
vertex_t	boost::graph_traits<graph_t>::vertex_descriptor
n_iter_t	boost::property_traits<embedding_t>::value_type ::const_iterator
n_range_t	std::pair<n_iter_t,n_iter_t>

Figure 6.5: Typedefinitions for Poh with Path Walking.

Type	Concept	Additional Requirements
graph_t	VertexAndEdgeListGraph	None
color_t	EqualityComparable, CopyAssignable	None
embedding_t	PlanarEmbedding	None
color_map_t	LvaluePropertyMap	value_type is color_t
mark_map_t	LvaluePropertyMap	value_type is an integer
n_range_map_t	LvaluePropertyMap	value_type is n_range_t
vertex_iterator_t	InputIterator	value_type is vertex_t

Figure 6.6: Template requirements for Poh with Path Walking.

Type	
<code>augmented_embedding_t</code>	a type modeling <code>AugmentedEmbedding</code>
<code>node_t</code>	<code>boost::property_traits&lt;augmented_embedding_t&gt;</code> <code>::value_type::value_type</code>
<code>iterator_t</code>	<code>boost::property_traits&lt;augmented_embedding_t&gt;</code> <code>::value_type::iterator</code>
<code>graph_t</code>	the type of the underlying graph
<code>vertex_t</code>	<code>boost::graph_traits&lt;graph_t&gt;::vertex_descriptor</code>

Figure 6.7: Types for the `AugmentedEmbedding` concept.

`planar_embedding`, similar to the neighbor range vertex property described in section 5. This allows us to do a single iteration through the neighbors of a vertex to get an “orientation”, then remember this orientation for the remainder of the algorithm.

Additionally, we optimize the implementation by combining the steps of (4.3) and (4.4). Notice the path that is colored in (4.4) is the same path we will walk through in a subsequent call to (4.3). We may therefore perform the marking and chord finding operations of (4.3) as the path is colored in (4.4). This reduces the number of times we visit a particular edge by a factor of 2.

## Augmented Embeddings

In this section we describe the `AugmentedEmbedding` concept used to store embedding ordered augmented adjacency lists for a graph.

The `AugmentedEmbedding` concept refines `LvaluePropertyMap`, placing additional restrictions on the `value_type` of the map. The types are described in figure 6.7. Valid expressions are described in figure 6.8.

The object `embedding` will assign a range of objects of type `node_t` to each vertex `v` in the underlying graph. There will be exactly one node in this range for each neighbor of `v` in the underlying graph. We will call this range of nodes the augmented adjacency list for `v`.

The type `node_t` will represent a neighboring vertex `u` in the augmented adjacency list for a vertex `v`. The type `iterator_t` will be an iterator for the range of `node_t` objects for a vertex `v`.

For a vertex `v` each node `n` in the range `embedding[v].begin()` to `embedding[v].end()` will have `n.vertex` be a neighboring vertex `u` and `n.iterator` be the unique iterator in the range `embedding[u].begin()` to `embedding[u].end()` such that `n.iterator->vertex` is equal to `v`.



Object(s)	Description
<code>u,v</code>	objects of type <code>vertex_t</code>
<code>embedding</code>	an object of type <code>augmented_embedding_t</code>
<code>n</code>	an object of type <code>node_t</code>

Figure 6.8: Notation for our discussion of augmented embeddings.

Expression	Type	Description
<code>n.vertex</code>	<code>vertex_t</code>	vertex member for the node <code>n</code>
<code>n.iterator</code>	<code>iterator_t</code>	iterator member for the node <code>n</code>
<code>embedding[v].begin()</code>	<code>iterator_t</code>	beginning of the range of nodes
<code>embedding[v].end()</code>	<code>iterator_t</code>	end of the range of nodes
<code>embedding[v].push_back(n)</code>	<code>void</code>	append <code>n</code> to the range of nodes
<code>embedding[v].clear()</code>	<code>void</code>	clear the range of nodes

Figure 6.9: Valid expressions for an object modeling `AugmentedEmbedding`.

```

template<
    typename graph_t ,
    typename embedding_t ,
    typename color_list_map_t ,
    typename n_range_map_t ,
    typename location_map_t ,
    typename face_iterator_t
>
void hartman_skrekovski_color(
    const graph_t & graph ,
    const embedding_t & augmented_embedding ,
    color_list_map_t & color_list_map ,
    n_range_map_t & neighbor_range_map ,
    location_map_t & face_location_map ,
    face_iterator_t face_begin , face_iterator_t face_end
);

```

Figure 6.10: Publicly visible function prototype for Hartman-Skrekovski.

Type	
<code>vertex_t</code>	<code>boost::graph_traits&lt;graph_t&gt;::vertex_descriptor</code>
<code>n_iter_t</code>	<code>boost::property_traits&lt;embedding_t&gt;::value_type</code> <code>::const_iterator</code>
<code>n_range_t</code>	<code>std::pair&lt;n_iter_t,n_iter_t&gt;</code>

Figure 6.11: Typedefinitions for Poh with Path Walking.

Type	Concept	Additional Requirements
<code>graph_t</code>	<code>VertexAndEdgeListGraph</code>	None
<code>color_t</code>	<code>EqualityComparable</code> , <code>CopyAssignable</code>	None
<code>embedding_t</code>	<code>PlanarEmbedding</code>	None
<code>color_list_t</code>	<code>SequenceContainer</code>	<code>value_type</code> is <code>color_t</code>
<code>color_list_map_t</code>	<code>LvaluePropertyMap</code>	<code>value_type</code> is <code>color_list_t</code>
<code>location_map_t</code>	<code>LvaluePropertyMap</code>	<code>value_type</code> is an integer
<code>n_range_map_t</code>	<code>LvaluePropertyMap</code>	<code>value_type</code> is <code>n_range_t</code>
<code>vertex_iterator_t</code>	<code>InputIterator</code>	<code>value_type</code> is <code>vertex_t</code>

Figure 6.12: Template requirements for Poh with Path Walking.

## Hartman-Skrekovski in the BGL

Here we detail our implementation of the Hartman-Skrekovski algorithm described in (5.3) and (5.4). The function prototype, type definitions, and template requirements are shown in figures 6.10, 6.11, and 6.12 respectively.

We assume the provided graph is simple and weakly triangulated and the given `augmented_embedding` structure represents a valid planar embedding of the graph. We assume the range of vertices is a cycle in the provided graph. We assume `color_list_map` assigns each vertex in the cycle a sequence of at 2 or more colors, and each vertex interior to the cycle a sequence of 3 or more colors. We also require that all vertices are initially assigned a location mark of 0 by `location_map`.

The implementation follows algorithms (5.3) and (5.4) with the following optimization. By combining the cases of (5.3) and (5.4) we may draw and remove the path simultaneously, one vertex at a time. In the implementation therefore perform the operations of both (5.3) and (5.4) simultaneously as each vertex is colored. This reduces the number of times we visit a particular edge by a factor of 2.

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