

# Multiple-source shortest paths with unit weights in embedded graphs

## Abstract

We describe a new algorithm that computes multiple-source shortest paths from vertices in a given boundary face to all other vertices in an embedded graph with unit weight edges.

## 1 Introduction

We can formally define multiple-source shortest paths problem as follows:

**Given.** Let  $G$  be a directed graph  $(V, \vec{E})$ , embedded on a surface with genus  $g$ . All edge weights are unit and  $|V| = n$ . Using Euler's theorem, we can derive  $|E| = n + 2g - 1$ .

**Find.** Consider boundary face  $f$  of  $G$ .  $\forall v \in f$ , find a shortest path to  $\forall u \in V$ .

Klein [15] described first algorithm to solve MSSP problem in planar graphs in  $O(n \log n)$ -time. Later, Cabello, Chamber, and Erickson [5] described an alternate algorithm and generalized it to graphs embedded in higher genus surfaces. Recently, Eisenstat and Klein [9] introduced a new algorithm to compute MSSP in planar graphs in linear time when edge weights are unit. Our paper attempts to generalize this idea to graphs embedded in higher genus surfaces. In their paper, Eisenstat and Klein use so-called leafmost pivoting rule to deal with possibility more than one pivots at the given time. However, there is no direct way to generalize a leafmost pivoting rule in graphs embedded in higher genus surfaces. In this paper, we describe ways to alleviate this difficulties and how to compute MSSP.

### 1.1 Definition and Notation

We adapt definitions and notations of surfaces, embedding, and duality from Cabello et al.'s paper [5]. Furthermore, we refer to graphs embedded on higher genus surfaces as “embedded graphs”.

## 2 Holy Tree

Let  $T$  be a breadth first search(BFS) tree of  $G$ , and  $C^*$  be a BFS co-tree in  $(G/T)^*$ . Then there is exactly  $2g$  leftover edges  $L = \{e_1, e_2, \dots, e_{2g}\}$ , according to the Euler's formula.

There exists a unique cycle  $\lambda_i$  in  $C^* \cup e_i$ , and  $(\lambda_1, \lambda_2, \dots, \lambda_{2g}) = \Lambda$  defining homology basis. We define homological signature of an edge as follows:

$$[e]_i = \begin{cases} 1 & , \text{if } e \in \lambda_i \\ -1 & , \text{if } rev(e) \in \lambda_i \\ 0 & , \text{o/w} \end{cases}$$

Furthermore, we define leafmost term  $\alpha$  recursively as follows:

$$\alpha(e^*) = \begin{cases} 1 & , \text{if } rev(e^*) \text{ is a leaf dart in } C^* \\ \sum_{tail(e'^*)=head(e^*)} \alpha(e'^*) & , \text{o/w} \end{cases}$$

We can extend above definition with  $\alpha(e) = \alpha(e^*)$  and  $\alpha(e)^* = -\alpha(rev(e^*))$ .

This leafmost term definition has been first introduced by Cunningham in ???.

Let  $\tilde{w}(e) = (1, [\vec{e}], \alpha(e))$  be new weight vector for each edge in  $G$ . We refer to each component this weight vector as length, homology, and leafmost terms respectively.

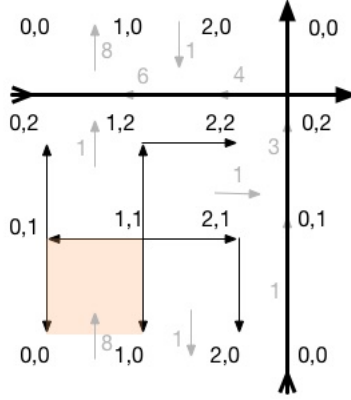


Figure 1: An example of holy tree in graph with genus 1.

**Definition.** An edge  $e_1$  is holier than  $e_2$ , if  $\tilde{w}(e_1) < \tilde{w}(e_2)$  in lexicographic comparison. Therefore, we can define holiness of any  $S \subset G$  as follows:

$$H(S) = \sum_{e \in S} \tilde{w}(e)$$

Note here that computing holy tree rooted at  $s$  immediately gives us single source shortest path tree rooted at  $s$  in our case.

We show an example figure for holy tree computation for a grid graph embedded in genus 1 surface. Notice that boundary edges are replicated for nice visual. Bold thick arrows represent homology cycles, grey arrows correspond to leafmost terms. Holy tree is rooted at  $(1, 1)$ .

## 2.1 Need of holiness

We provide a simple explanation on why it is necessary to introduce holiness to cope with ambiguity.

1. Leafmost term definition is not enough. This is because leftover  $2g$  edges could still cause ambiguity when computing shortest paths.
2. By introducing homology terms, we avoid this ambiguity.

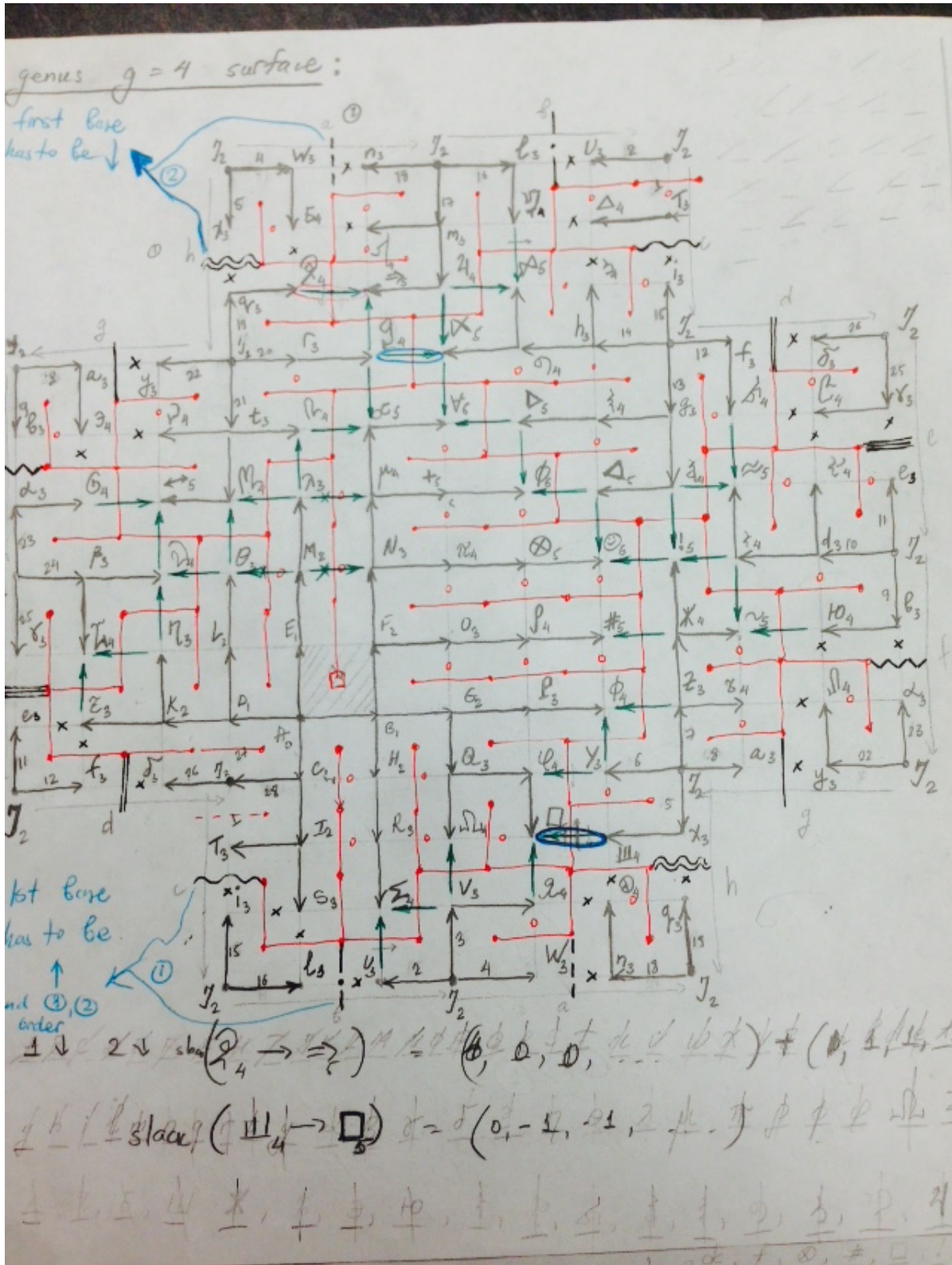
## 2.2 Leftmost tree vs Holy tree

1. Explain our initial attempts on leafmost tree maintaining to show it is NOT sufficient for dealing with non-unique shortest paths.

Klein [15] uses a notion of leftmost tree to resolve ambiguity when computing MSSP. Our initial hope was that even in higher genus surfaces leftmost tree and holy tree would be equal. However, on genus  $g = 4$  surface, we show that no choice of homology and leafmost terms can result in equal holy and leftmost trees. Consider below picture,

- Leftmost tree is rooted at  $A$  and denoted by solid black darts.
- There are exactly 8 homology cycles, each specifically denoted with special darts crossing the boundaries.
- Leafmost term building tree is denoted with red darts.

The observation on the figure is 2 darts highlighted in blue will be tense, regardless of the homology and leafmost choice configurations.



### 3 Initial holy tree

Holiest tree is a spanning tree with minimal holiness. We build holiest tree rooted at  $r$ , using slight tweak in the Bellman-Ford algorithm for finding shortest path tree rooted at  $r$ .

**BuildHoliestTree**( $G, \tilde{w}, r$ ):

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Set  $dist[r] \leftarrow (0, [\vec{0}], 0)$ 
 $pred(r) \leftarrow \text{NULL}$ 
for all  $v : v \neq r$ 
   $dist[v] \leftarrow (\infty, [\vec{\infty}], \infty)$ 
   $pred(v) \leftarrow \text{NULL}$ 
put  $r$  into queue
while queue is not empty:
  Let  $u \leftarrow$  dequeue item
  for all  $u \rightarrow v$ 
    if  $v$  is not marked
      mark  $v$  and put in the queue
    if  $isTense(u \rightarrow v)$ 
      relax( $u \rightarrow v$ )

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**isTense**( $u \rightarrow v$ ):

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return  $dist[u] + \tilde{w}(u \rightarrow v) < dist[v]$ 

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**relax**( $u \rightarrow v$ ):

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 $dist[v] \leftarrow dist[u] + \tilde{w}(u \rightarrow v)$ 
 $pred[v] \leftarrow u$ 

```

**Observation.** Each vertex will be added once to the queue.

**Corollary.** Each edge will be relaxed at most once.

**Lemma 2.1.** If there is no tense edge in  $G$ , then for each  $v : r \rightarrow \dots \rightarrow pred(pred(v)) \rightarrow pred(v) \rightarrow v$  is the holiest path from  $r$  to  $v$ .

**Proof:** Let's prove it by induction on  $dist[v].length$  distance from the root  $r$ .

**Base.**  $dist[v].length = 0$ , then  $v = r$ , so the claim holds trivially.

**Induction Step.** Suppose the claim is true for all vertex  $v \in V$  such that  $dist[v].length < d$  for some  $d$ . Consider vertex  $v$  such that  $dist[v].length = d$ . By induction hypothesis, all vertices with  $dist[u].length = d - 1$  have holiest path correctly updated. By definition,  $dist[v] = \min_{u \rightarrow v} \{dist[u] + \tilde{w}(u \rightarrow v)\}$ , here  $dist[u].length = d - 1$ . By Induction hypothesis,  $dist[u]$  is not tense and can construct holiest path to  $u$ , so if there is no tense edge in  $G$  then  $dist[v] = \min\{dist[u] + \tilde{w}(u \rightarrow v)\}$  holds.

□

**Corollary.** The algorithm will produce holiest tree rooted at  $r$  in  $O(n + g)$  time.

### 4 Moving Along an Edge

Let  $T_u$  be a current holiest tree,  $u \rightarrow v$  be an edge that we are trying to move along. So at the end of the process we would like to obtain  $T_v$ , the holiest tree rooted at  $v$ .

We follow Cabello, Chambers, and Erickson's [5] method to move across the edge, by bisecting the given edge and inserting new source  $s$  which is connected to both  $u$  and  $v$ . At the start of the process,  $s == u$  and continuously move to  $v$ , and when  $s == v$ , we would have our  $T_s = T_v$ .

**Initial attempt:**

Let  $(1, \vec{h}, \alpha) = w(u \rightarrow v)$ . We treat  $\lambda$  as a parameter with satisfying following equations:

$$w_u(s \rightarrow u) = (0, [\vec{0}], 0), \quad w_u(s \rightarrow v) = (1, \vec{h}, \alpha) \quad (1)$$

$$w_v(s \rightarrow u) = (1, -[\vec{h}], -\alpha), \quad w_v(s \rightarrow v) = (0, \vec{0}, 0) \quad (2)$$

The natural definition would be as follows, but it does not satisfy our constraints (1) – (2).

$$w_\lambda(s \rightarrow u) = (\lambda, [\vec{0}], 0) \quad (3)$$

$$w_\lambda(s \rightarrow v) = (1 - \lambda, \vec{h}, \alpha) \quad (4)$$

Therefore, we modify our parametric definition by decreasing distance to  $u$  by  $w(u \rightarrow v) = (0, -[\vec{h}], -\alpha)$ . This change allows us to define

$$w_\lambda(s \rightarrow u) = (0, -[\vec{h}], -\alpha) + \lambda * (1, [\vec{h}], \alpha) \quad (5)$$

$$w_\lambda(s \rightarrow v) = (1, [\vec{h}], \alpha) + \lambda * (1, [\vec{h}], \alpha) \quad (6)$$

Since we decrease distance to  $u$  at the start, this could potentially introduce pivots. Suppose, for instance,  $x$  be descendant of  $u$  and  $y$  be of  $v$  in  $T_s$ , then:

$$\begin{aligned} \text{slack}(x \rightarrow y) &= \text{dist}(x) + w(x \rightarrow y) - \text{dist}(y) = \\ &= \text{dist}_0(x) + (0, -[\vec{h}], -\alpha) + w(x \rightarrow y) - \text{dist}_0(y) = \\ &= \text{slack}_0(x \rightarrow y) + (0, -[\vec{h}], -\alpha) \Rightarrow \\ \text{slack}(x \rightarrow y) &< 0, \text{ if } \text{slack}_0(x \rightarrow y) < (0, [\vec{h}], \alpha) \end{aligned}$$

Therefore, this could be potentially problematic. Furthermore, **What if  $u \rightarrow v$  has non-trivial homology or leafmost term?**

1. First attempt of not maintain holy tree at all times.
2. Second attempt of continuously moving by changing homology and leafmost terms, also reducing destination distance initially.
3. Necessity of resolving homology and leafmost values for an edge that source is moving.

We need to take into account that  $u \rightarrow v$  has non-trivial homology and leafmost terms  $[\vec{h}], \alpha$ . To deal with the problem of potential non-trivial homology edge splitting process, we reduce distances to  $u$  and  $v$  as follows:

$$w_\epsilon(s \rightarrow u) = (0, -[\vec{h}], -\alpha) \quad (7)$$

$$w_\epsilon(s \rightarrow v) = (1, [\vec{0}], 0) \quad (8)$$

This process can explained in following way:

1. When we split  $uv$  to 2 edges  $(us, sv)$ , we assume  $[\vec{h}], \alpha$  terms reside in  $sv$  side of  $uv$  at the start.
2. By reducing weight of  $w(s \rightarrow v)$  by  $(0, -[\vec{h}], -\alpha)$ , we are removing homology and leafmost terms from  $sv$  edge.
3. Then we add those values to  $su$ , which is equivalent to adding  $(0, -[\vec{h}], -\alpha)$  to dart  $w(s \rightarrow u)$ .

Since we reduced distance to all vertices in the graph by equal amount (this is because each vertex is either child of  $u$  or  $v$  in  $T_s$ , so reducing distances to  $u$  and  $v$  is same as reducing distances to all vertices), the process does not introduce any pivots. We define a parametric weights as follows:

$$w_\lambda(s \rightarrow u) = (0, -[\vec{h}], -\alpha) - \lambda \quad (9)$$

$$w_\lambda(s \rightarrow v) = (1, [\vec{0}], 0) + \lambda \quad (10)$$

Every other dart  $x \rightarrow y$  has constant parametric weight  $w_\lambda(x \rightarrow y) = w(x \rightarrow y)$ . We then maintain the holy tree  $T_\lambda$  rooted at  $s$ , with respect to the weight function  $w_\lambda$ , as  $\lambda$  increases continuously from 0 to  $(1, [\vec{0}], 0)$ . When  $\lambda = w(u \rightarrow v)$ ,  $T_\lambda = T_v$ .

In the following algorithm, **pred** defines holy tree rooted at  $u$ , and **dist** is corresponding distance to each vertex in the graph.

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MoveAlongEdge( $G, u \rightarrow v, dist, pred$ ):
  Add new vertex  $s$ 
   $pred[u], pred[v] \leftarrow s$ 
   $\lambda \leftarrow 0$ 

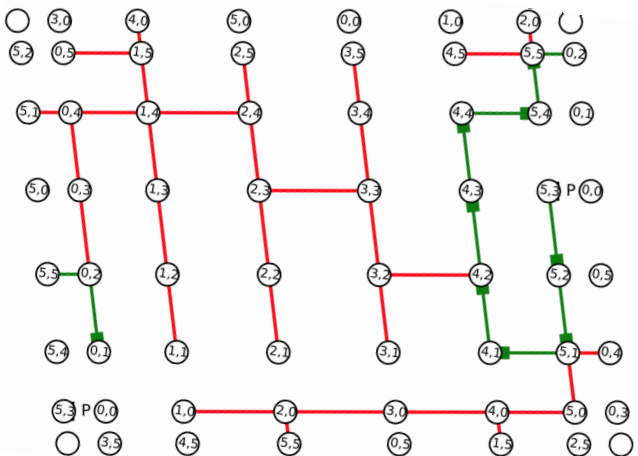
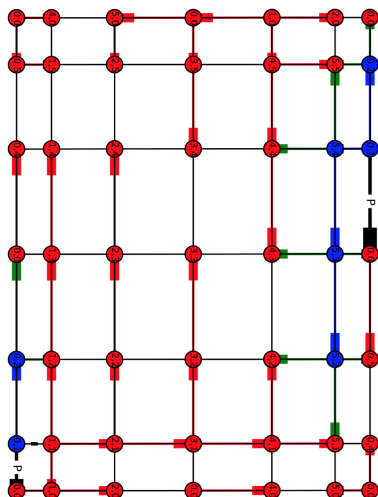
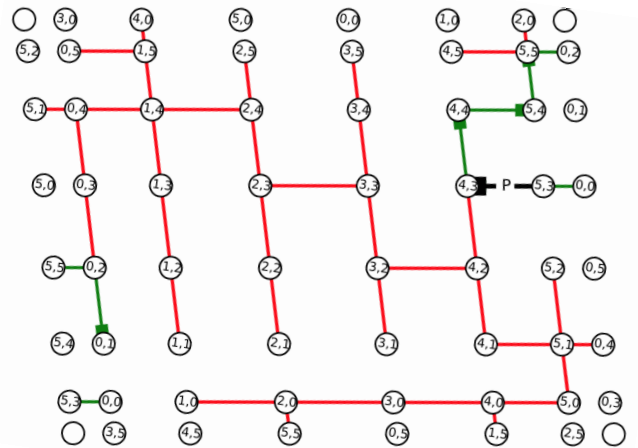
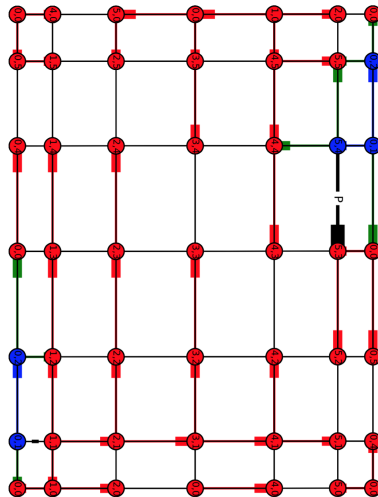
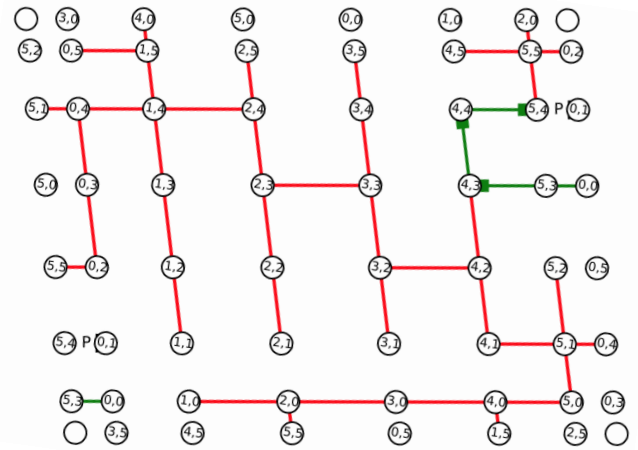
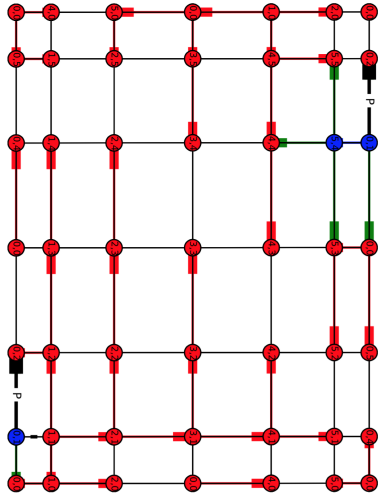
   $w(s \rightarrow u) \leftarrow (0, -[w(s \rightarrow u)], -\alpha(w(s \rightarrow u)))$ 
  AddSubtree( $(0, -[w(s \rightarrow u)], -\alpha(w(s \rightarrow u)))$ ,  $u$ )

   $w(s \rightarrow v) \leftarrow (1, [\vec{0}], 0)$ 
  AddSubtree( $(0, -[w(s \rightarrow u)], -\alpha(w(s \rightarrow u)))$ ,  $v$ )

  while  $\lambda < (1, [\vec{0}], 0)$ :
    pivot  $\leftarrow$  FindNextPivot
    If pivot is non NULL AND  $(\lambda + slack(\mathbf{pivot})/2) < (1, [\vec{0}], 0)$ 
      Pivot(pivot)
       $\lambda \leftarrow \lambda + slack(\mathbf{pivot})/2$ 
    else
       $\delta = (1, [\vec{0}], 0) - \lambda$ 
      AddSubtree( $\delta$ ,  $u$ )
      AddSubtree( $-\delta$ ,  $v$ )
       $\lambda \leftarrow \lambda + \delta$ 

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Below, we show an example of moving along an edge process on genus  $g = 2$  grid. On a left side, we see primal holy tree  $H$  with nodes increasing in distance are red, decreasing are blue, and next pivot is denoted as  $P$ . On right side, we see the dual graph  $(G/T)^*$  and active darts are noted with green color.





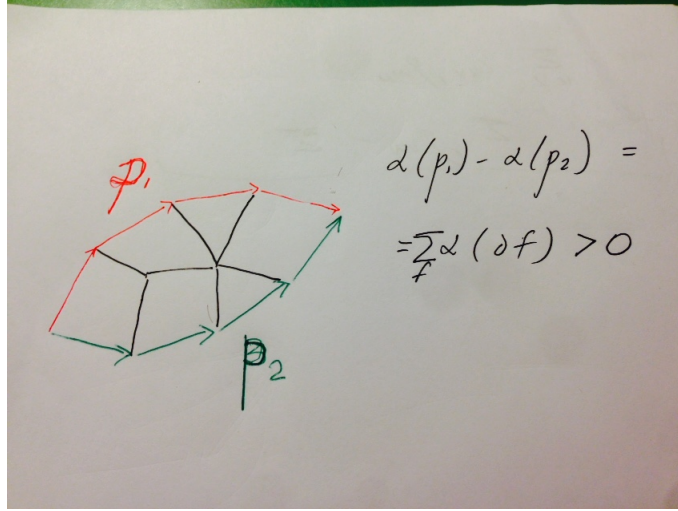
## 5 Bounding number of pivots

1. Describe how Eisenstat Klein clock lemma works and why it is not easily generalizable in higher genus graphs.

We introduce a clocking lemma to prove that each edge is involved in pivoting process at most  $O(g)$  times.

**Lemma 4.1.** Let  $v_0$  be a first vertex in our given face  $f$ , and  $v_i$  be the source right after  $i^{th}$  pivot. Consider a vertex  $y$ . We denote holiest path from  $v_i$  to  $y$  as  $P_i^y$ . Then  $P_i^y$  and  $P_j^y$  are non-crossing for all  $i, j$ .

**Proof:** Consider the following picture:



By the definition of  $\alpha$ :

$$\alpha(p_1) - \alpha(p_2) = \sum_f \alpha(d_f) > 0$$

This will ensure that any two paths  $p_1, p_2$ , whose  $w(p_1) = w(p_2)$  and  $[p_1]_\Lambda = [p_2]_\Lambda$ , has  $\alpha(p_1) \neq \alpha(p_2)$  □

**Lemma 4.2.** As source vertex  $s$  moves around the given face  $f$ , any dart  $d$  has exactly  $2g$  continuous clock state:

$$\begin{aligned} d &\in T \\ d^* &\in (G/T)^* \\ rev(d) &\in T \\ rev(d^*) &\in (G/T)^* \end{aligned}$$

**Proof:** Here is the proof. □

**Theorem 4.1.** Total running time of MSSP is  $O(gn)$ .

**Proof:** Building initial holy tree takes  $O(n + g)$  time. The process of moving around the face and pivoting takes  $O(gn)$  as each dart enters and replaces  $O(g)$  times. □

## 6 Finding pivot quickly

- What data structure do we maintain in the  $G^*$ ? Finding shortest path in network can also be understood as a Linear Programming problem as follows:
- How do we find next pivot quickly using above structure?



## 7 Analysis

- Building initial tree
- Pivoting
- Number of times each edge is pivoted
- Overall running time

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