Flips in Edge-Labelled Triangulations

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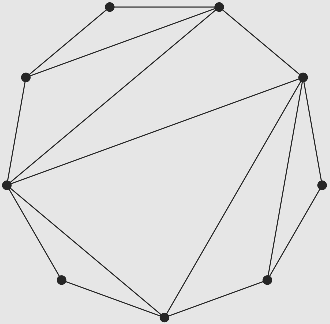
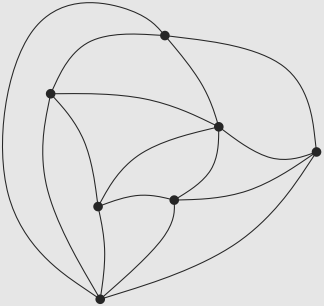
Triangulations

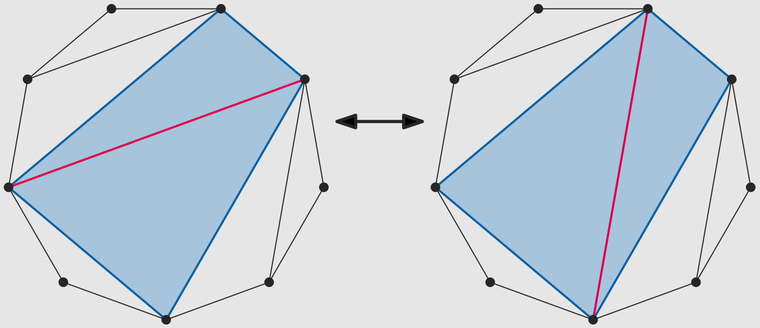
- Graphs where all faces are triangles





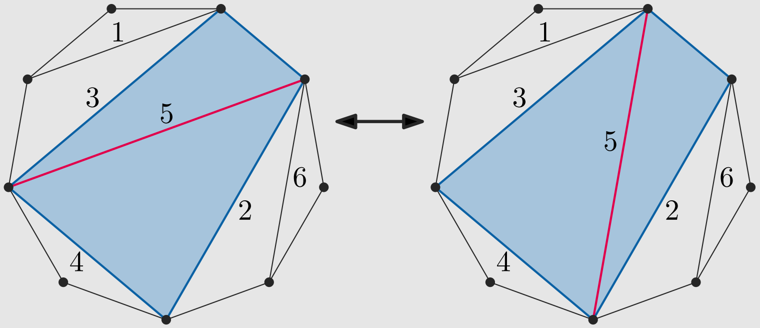
Flips

- Replace edge by other diagonal of quadrilateral



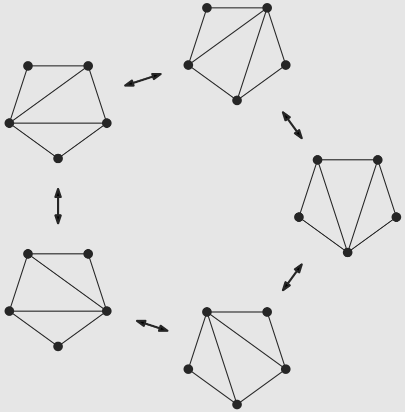
Flips

- Replace edge by other diagonal of quadrilateral
- Diagonals have unique labels



Flip graphs

- Vertex = triangulation, Edge = flip



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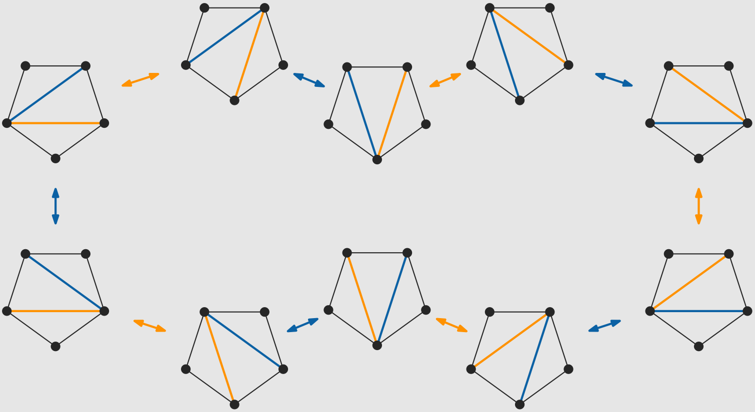

History

- Introduced by Wagner in 1936
  - Flip graph of combinatorial triangulations is connected
- Diameter:
  - $O(n^2)$ — Wagner, 1936

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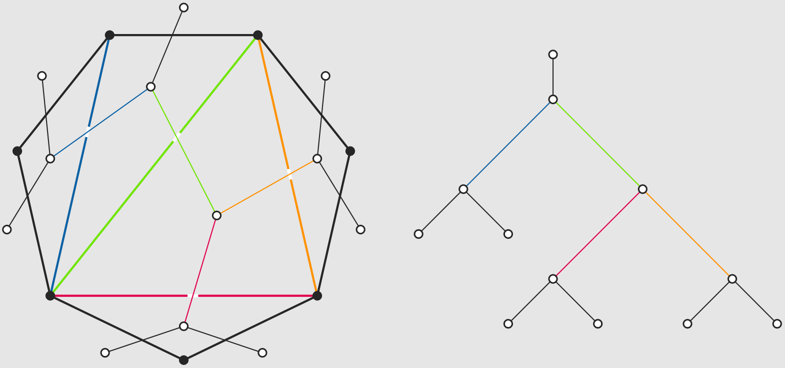
  - $O(n)$ — Sleator et al., 1992
  - $8n - O(1)$ — Komuro, 1997
  - $6n - O(1)$ — Mori et al., 2001
  - $5.2n - O(1)$ — Bose et al., 2014
  - $5n - O(1)$ — Cardinal et al., 2015

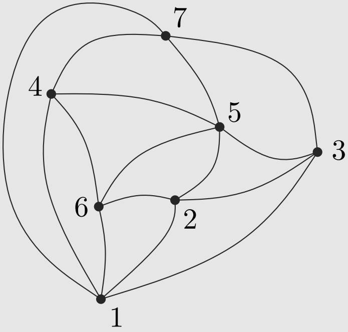
History

- Triangulation of convex polygon = binary tree
- Diameter $= 2n - 10$ — Sleator et al., 1988



History

- What happens when the vertices are labelled?
  - Diameter is $\Theta(n \log n)$ - Sleator et al., 1992



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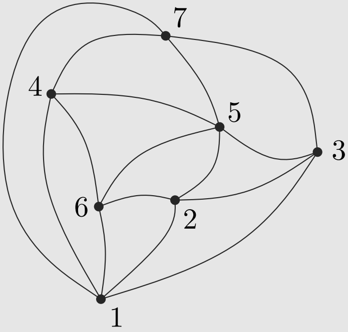
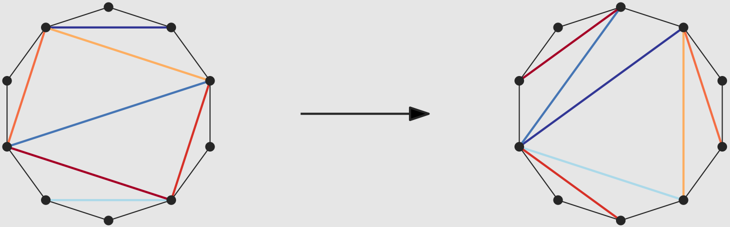


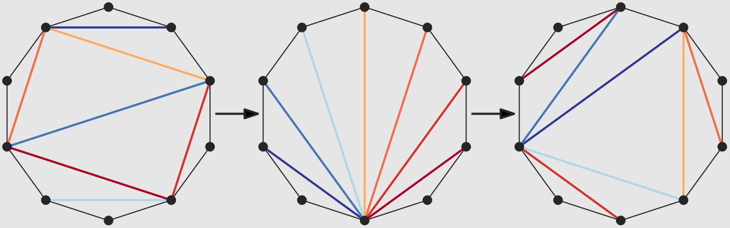
Upper bound

- Transform T_1 into T_2



Upper bound

- Transform T_1 into T_2
- Via canonical form T_C



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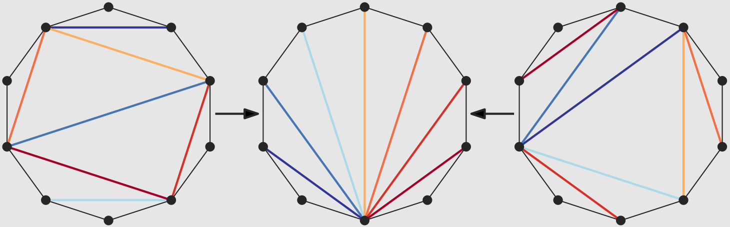
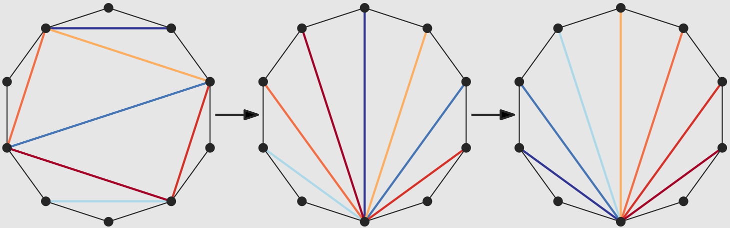


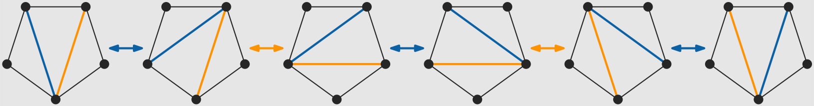
Transform into canonical

- Ignore labels
- Sort



Sorting

- We can exchange adjacent diagonals



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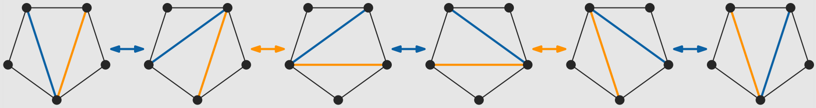

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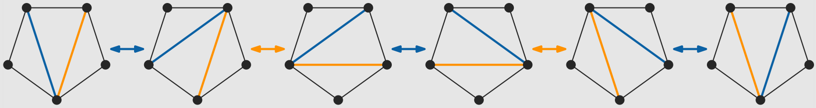

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  - Flip graph is connected!
  - Diameter is $O(n^2)$

Sorting

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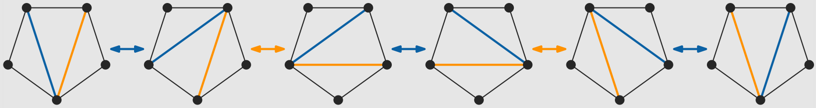
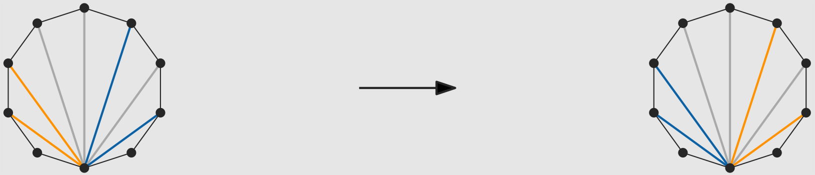


- We can do insertion sort
  - Flip graph is connected!
  - Diameter is $O(n^2)$
- Can we do better?

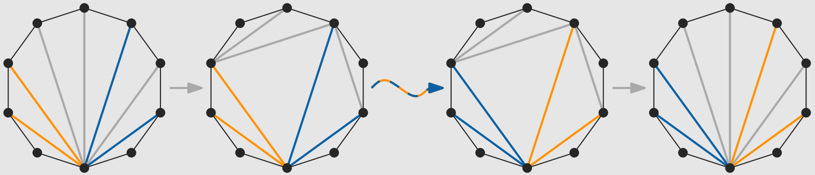
Quicksort

- Partition on the median



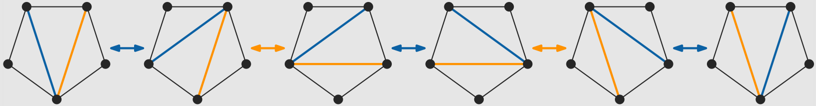
Quicksort

- Partition on the median
- Flip all neutral edges
- Reverse
- Recurse



Reverse

- Reversing two edges is easy:



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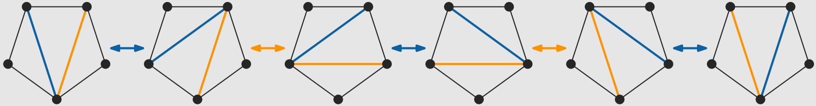
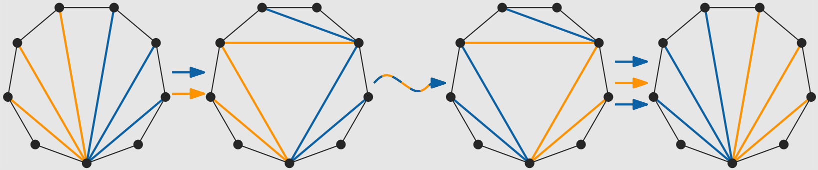


- Reversing more:
  - Flip middle pair “up”
  - Recurse on the rest
  - Reverse middle pair



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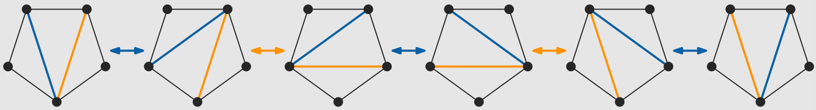
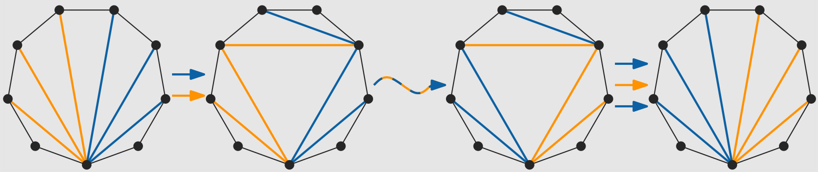


- Reversing more:
  - Flip middle pair “up” – $O(1)$
  - Recurse on the rest – $T(n-2)$
  - Reverse middle pair – $O(1)$

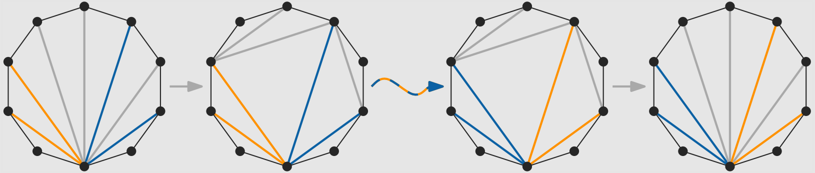
$= O(n)$ flips total



Quicksort

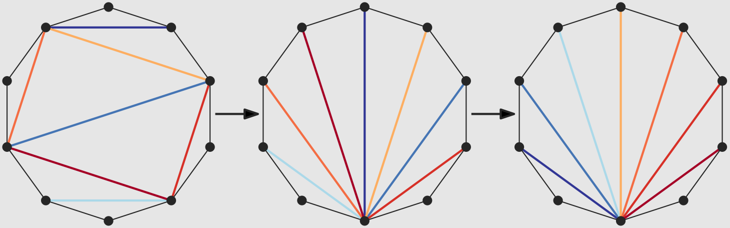
- Partition on the median
- Flip all neutral edges — $O(n)$
- Reverse — $O(n)$
- Recurse — $2T(n/2)$

$= O(n \log n)$ flips total



Transform into canonical

- Ignore labels — $O(n)$
- Sort — $O(n \log n)$



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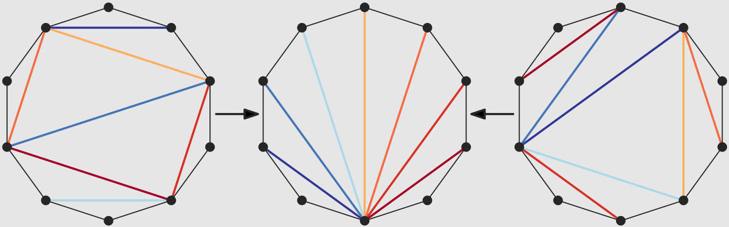

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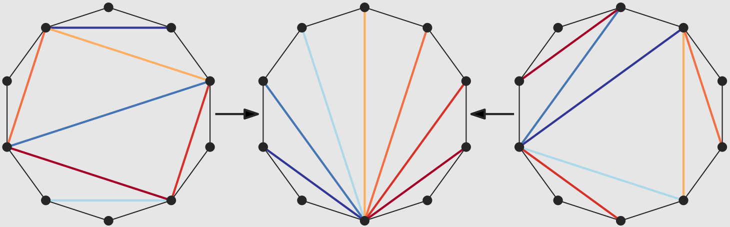

Lower bound

Theorem (Sleator, Tarjan, and Thurston, 1992)

Given a triangulation T of a convex polygon, the number of triangulations reachable from T by a sequence of m flips is at most $2^{O(n+m)}$, regardless of labellings.

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- There are over $n!$ edge-labelled triangulations:

$$\begin{aligned} 2^{O(n+d)} &\geqslant n! \\ O(n+d) &\geqslant \log n! \\ d &\geqslant \Omega(n \log n) \end{aligned}$$

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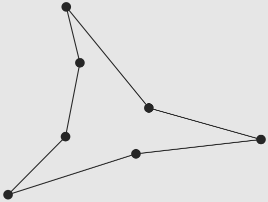
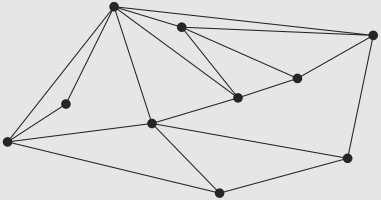
Theorem

The diameter of the flip graph is $\Theta(n \log n)$.

Pseudo-triangulations

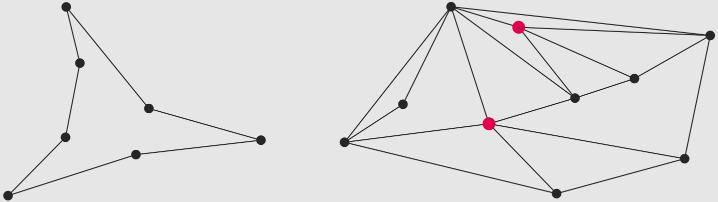
- All faces are pseudo-triangles





Pseudo-triangulations

- All faces are pseudo-triangles
- Pointed: all vertices are incident to a reflex angle ($> \pi$)



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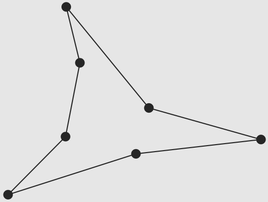
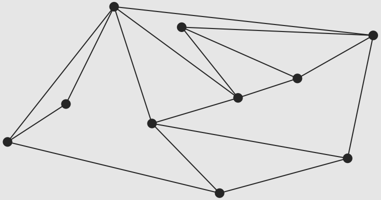
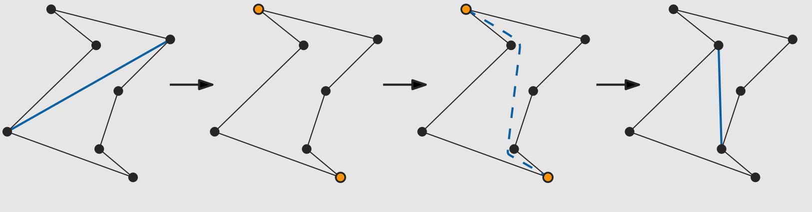




Flips

- Remove edge, leaving a pseudo-quadrilateral
- Find corners opposite removed edge
- Insert connecting geodesic



Previous work

Theorem (Bereg, 2004)

Any pointed pseudo-triangulation can be transformed into any other with $O(n \log n)$ flips.

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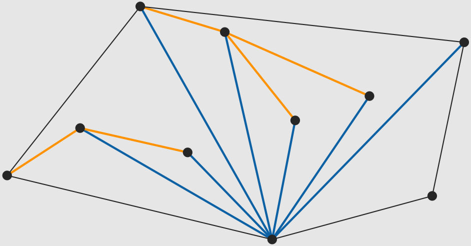
- What happens when edges are labelled?

Left-shelling pseudo-triangulation

- Add vertices in clockwise order around bottom vertex
  - Connect to bottom (bottom edge)
  - Add tangent to convex hull (top edge)



Left-shelling pseudo-triangulation

- Add vertices in clockwise order around bottom vertex
  - Connect to bottom (bottom edge)
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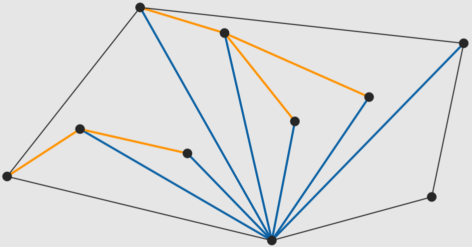
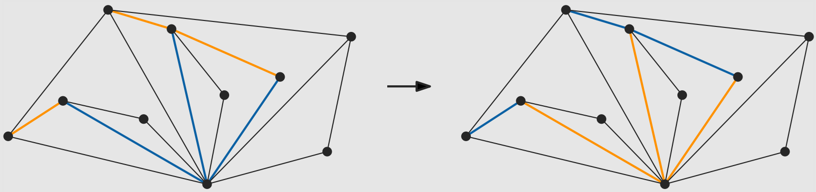
- This is our canonical form
- Problem reduces to sorting labels

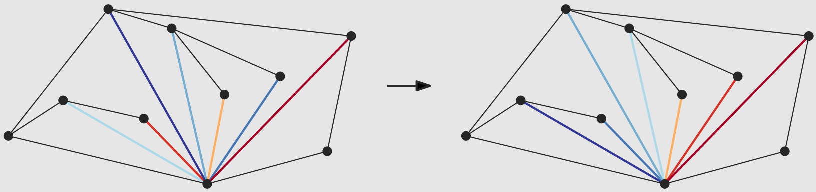


Tools

- *Sweep*: exchange labels on top and bottom pairs

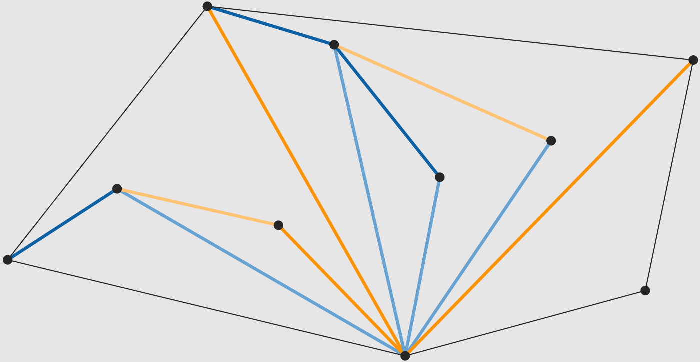


- *Shuffle*: reorder bottom labels



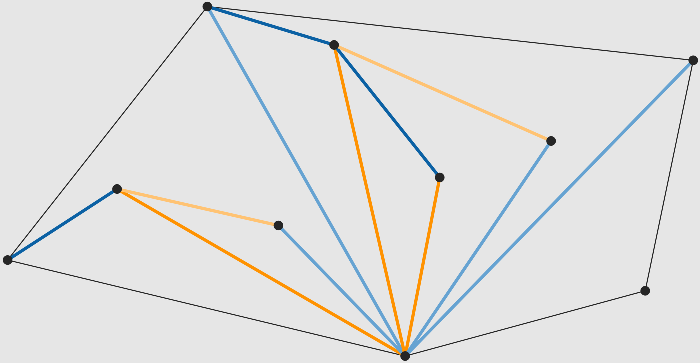
Algorithm

- Identify out-of-place top and bottom labels



Algorithm

- Pair these up (*Shuffle*)



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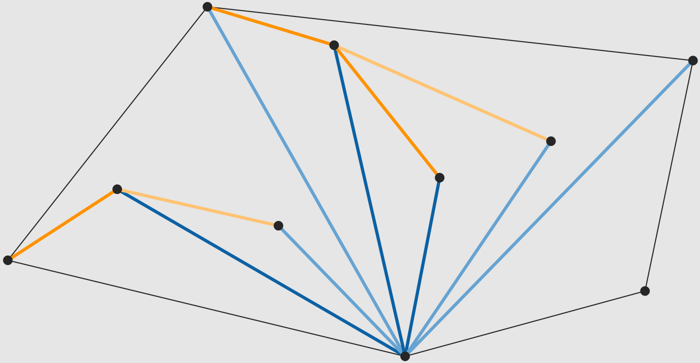
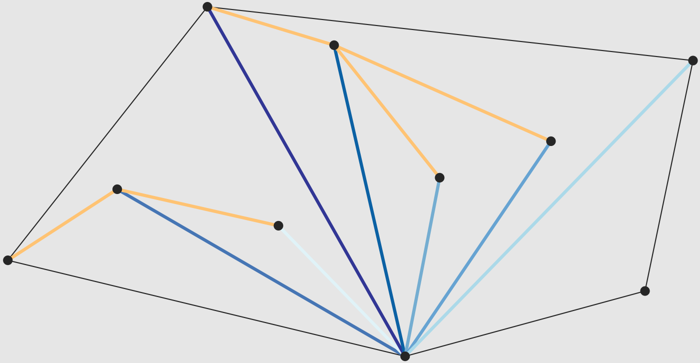
- Exchange them (*Sweep*)



Algorithm

- Sort bottom labels (*Shuffle*)



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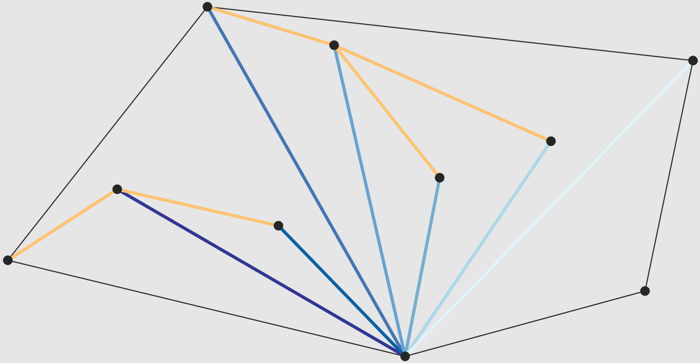
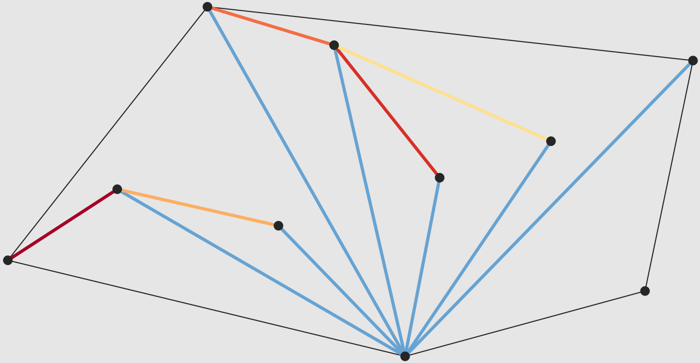


Algorithm

- Move all top labels down (*Sweep*)



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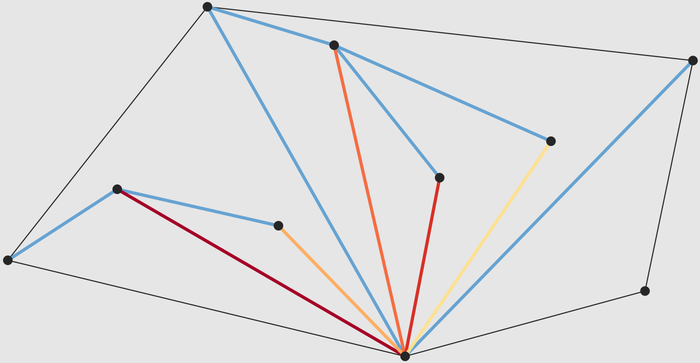

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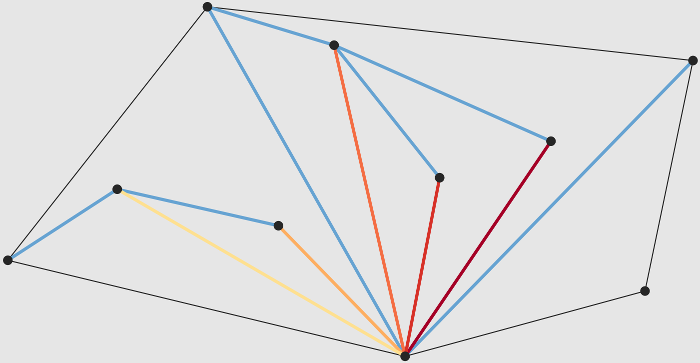
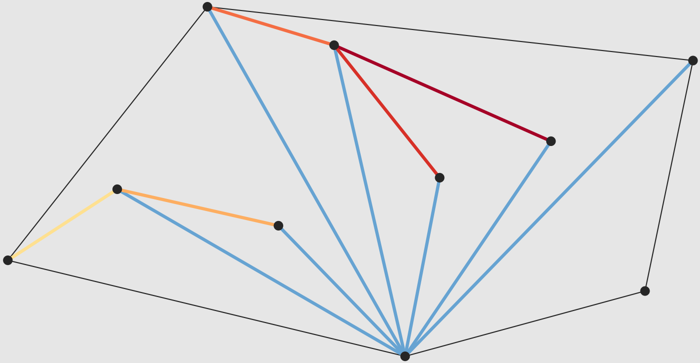


Algorithm

- Move them back (*Sweep*)



Upper bound

Theorem

We can sort the labels of a left-shelling pseudo-triangulation with $O(1)$ shuffles and sweeps.

Upper bound

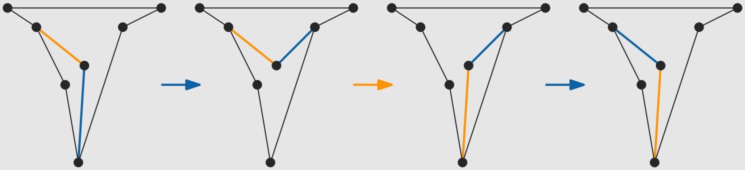
Theorem

We can sort the labels of a left-shelling pseudo-triangulation with $O(1)$ shuffles and sweeps.

- How do we shuffle and sweep?

Sweep

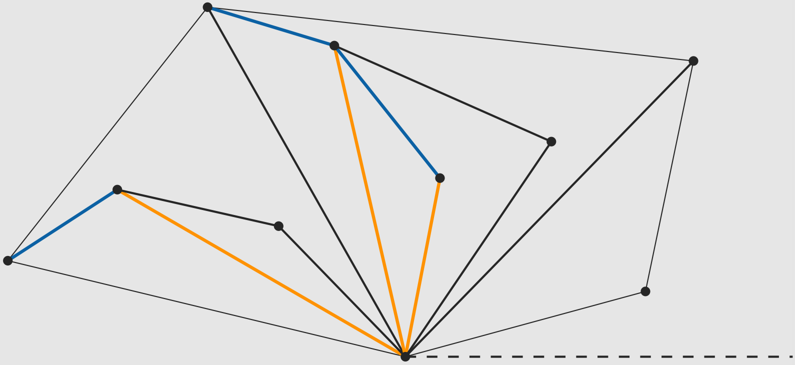
- Easy for degree-2 vertices:



- Idea: make every vertex degree-2 at some point

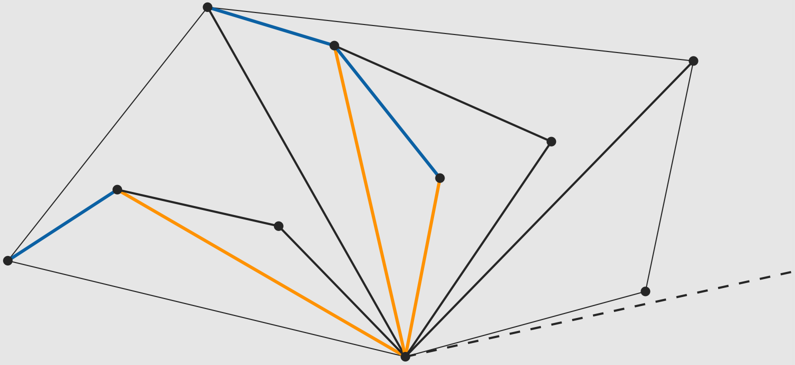
Sweep

- Shoot a ray from v_{bottom} to the right



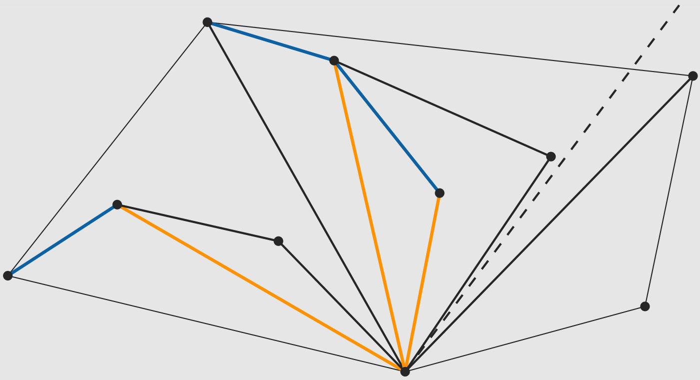
Sweep

- Sweep it counter-clockwise through the point set



Sweep

- When it passes a vertex:
  - Swap the top and bottom edge, if necessary
  - Flip the top edge



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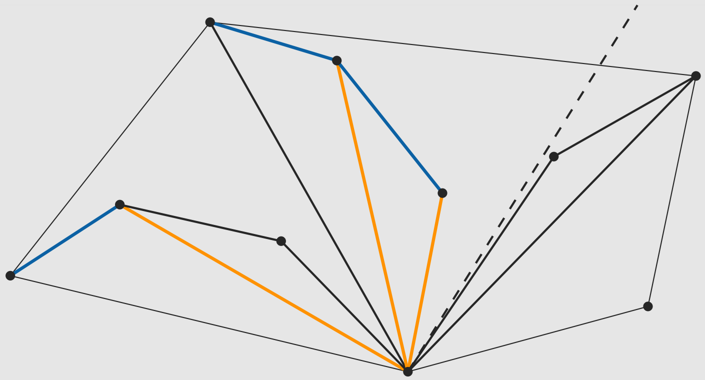

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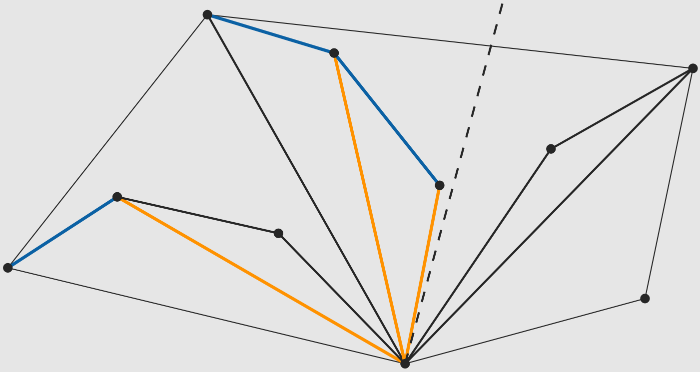

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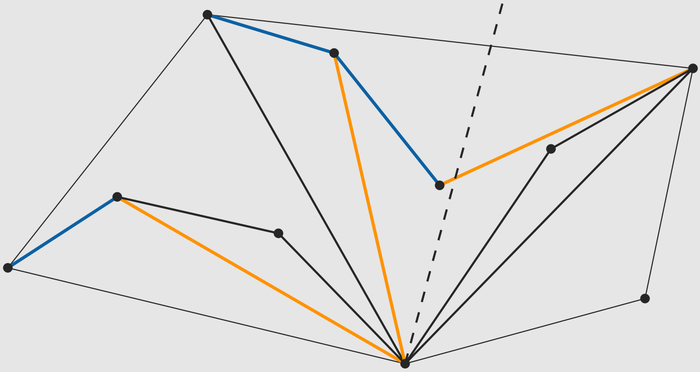

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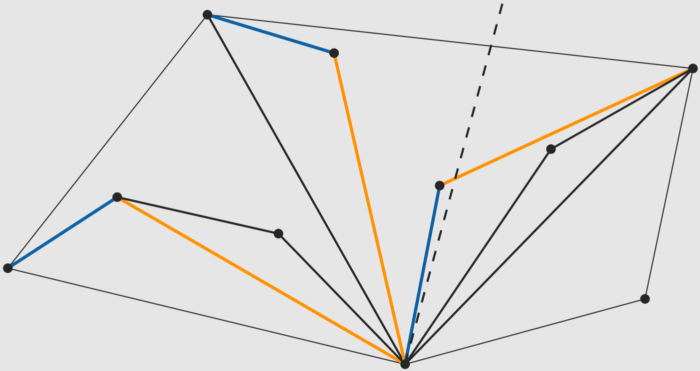

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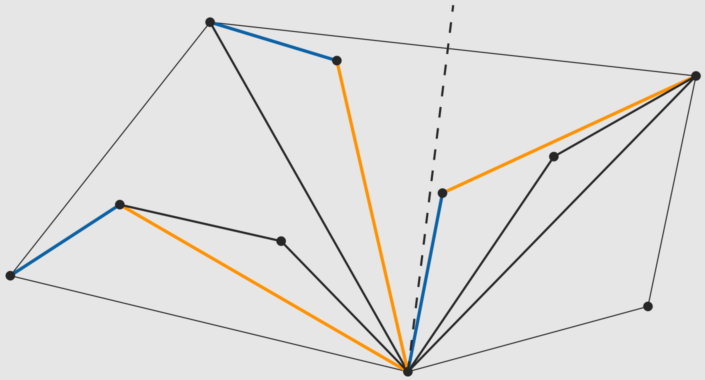

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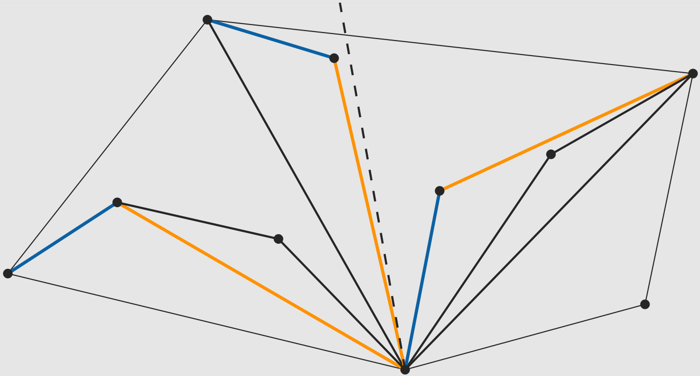

Sweep

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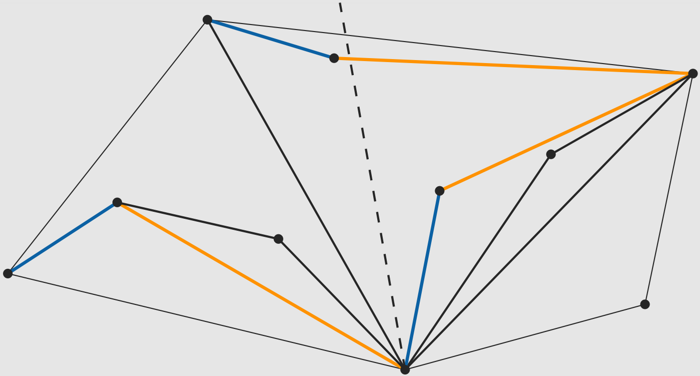

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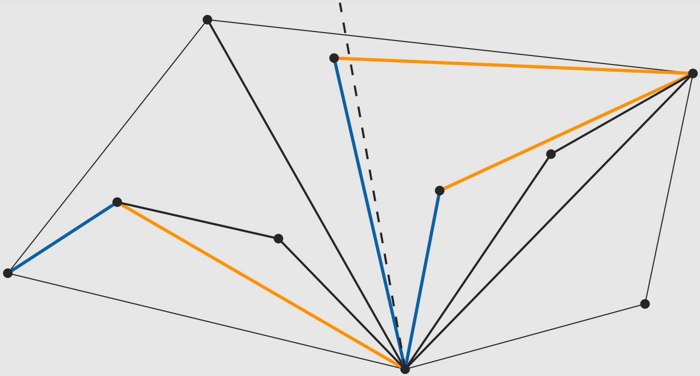

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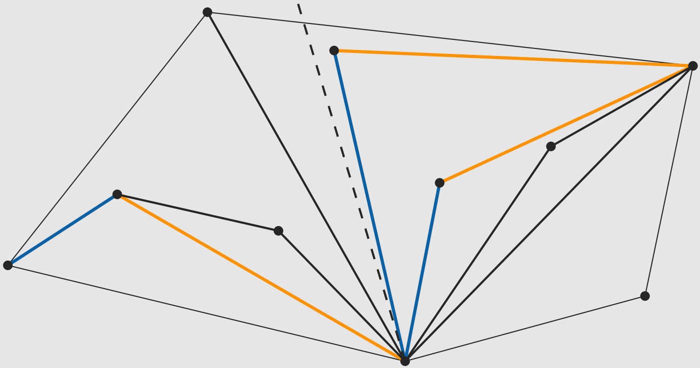

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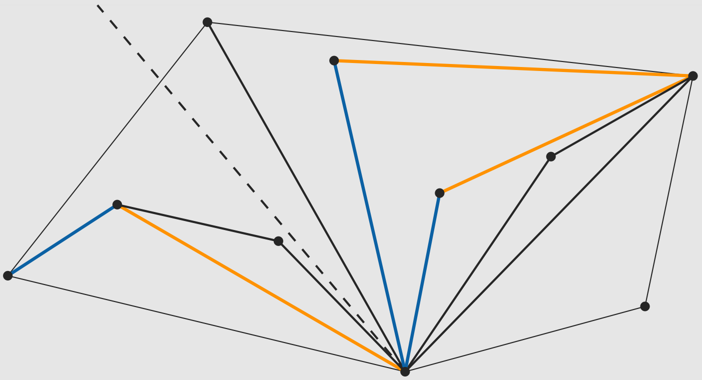

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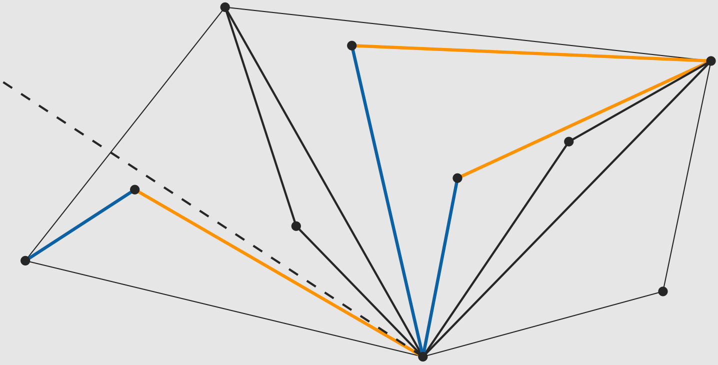

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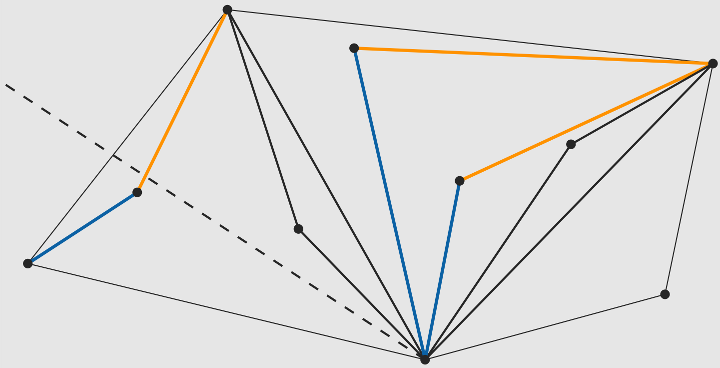

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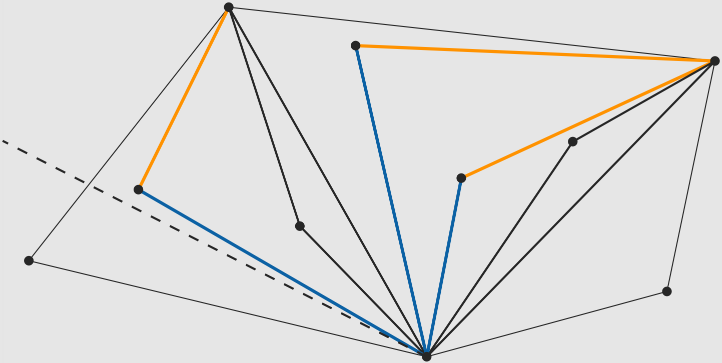

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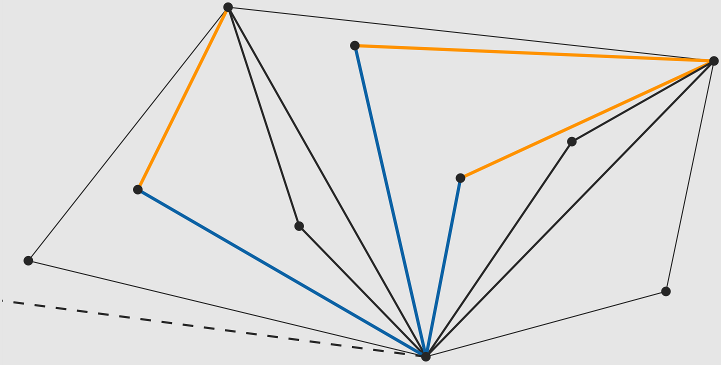

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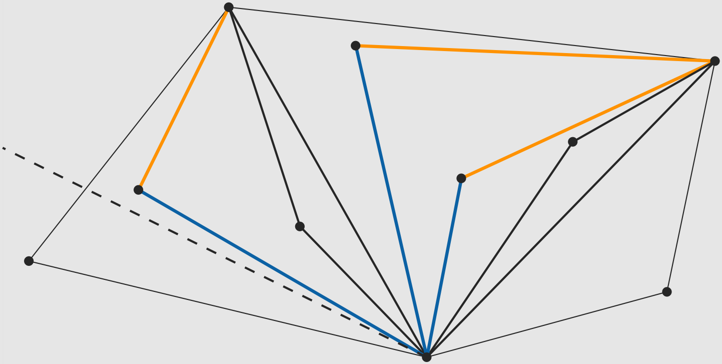

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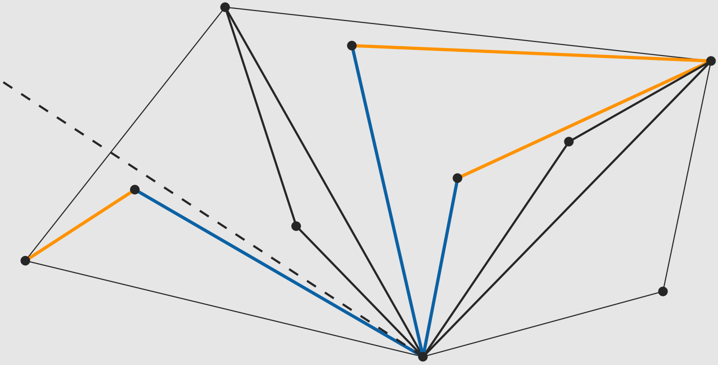

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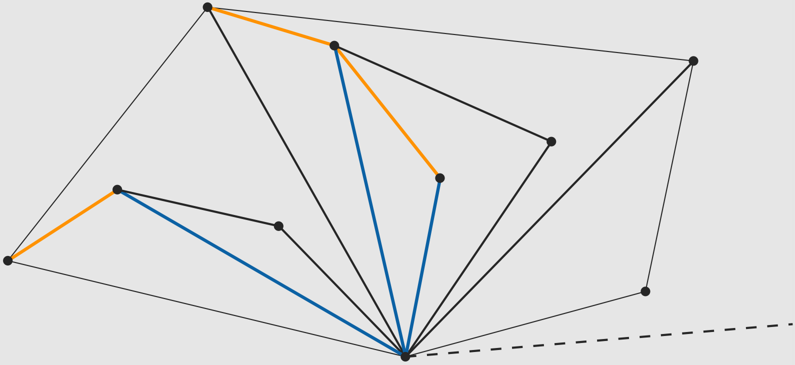
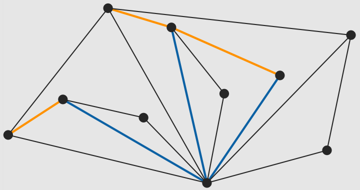
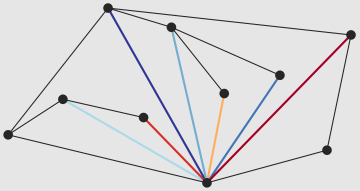


Tools

- *Sweep*: exchange labels on top and bottom pairs — $O(n)$



- *Shuffle*: reorder bottom labels



Shuffle

- Base case: can we swap the diagonals of a pseudo-pentagon?

Shuffle

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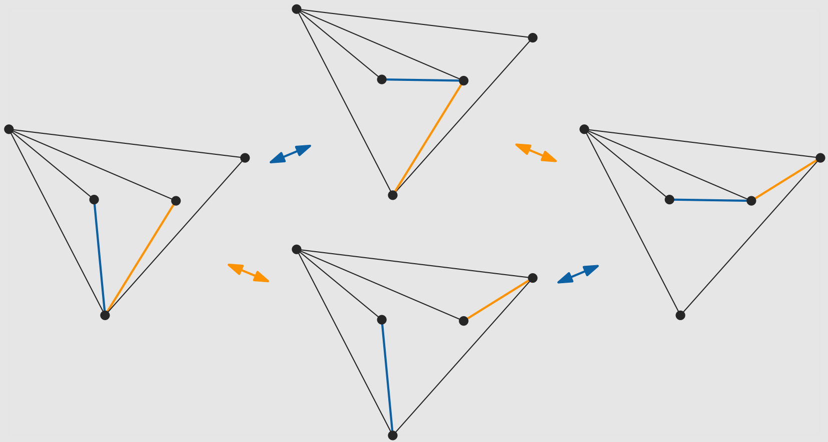
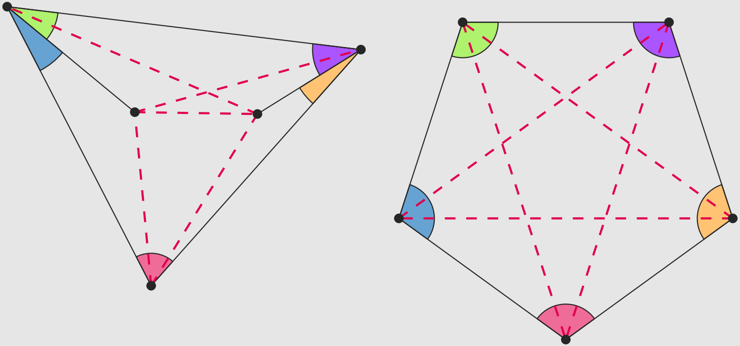
- Not always!



Shuffle

- Possible iff the pseudo-pentagon has five bitangents



Shuffle

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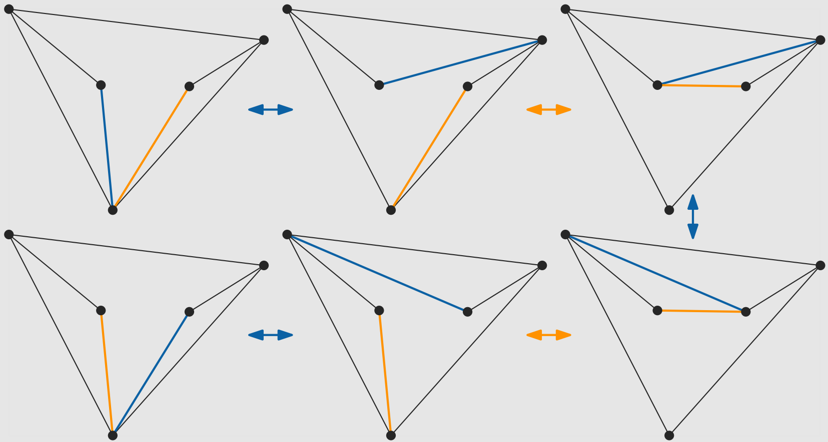
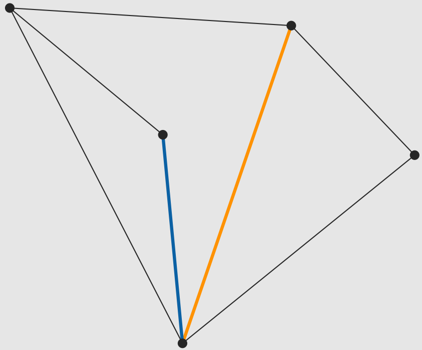


Shuffle

- This is enough:



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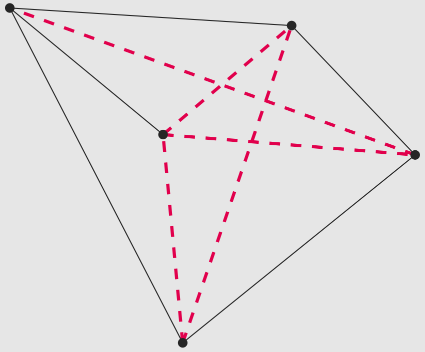

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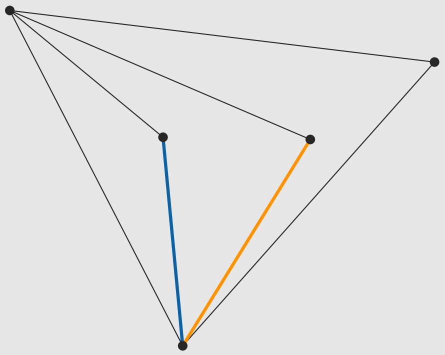

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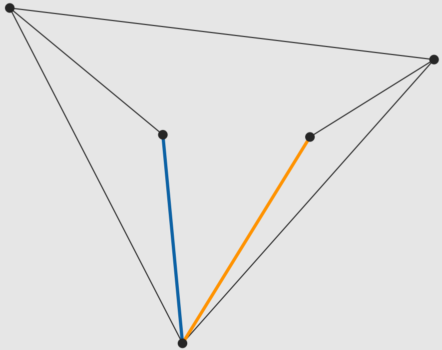

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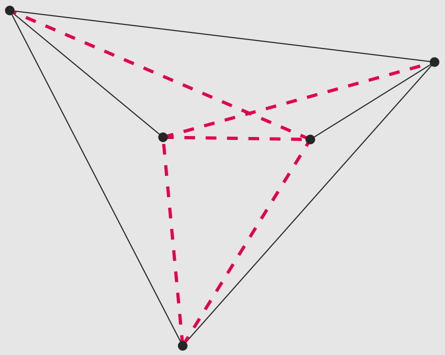

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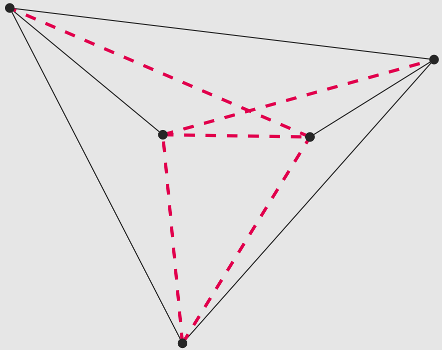
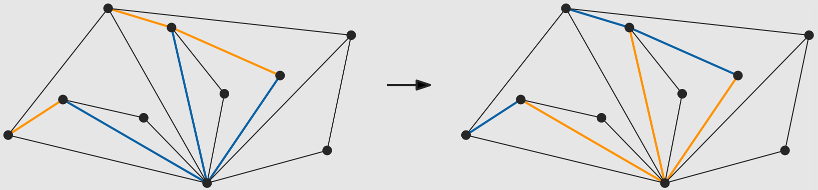


Theorem

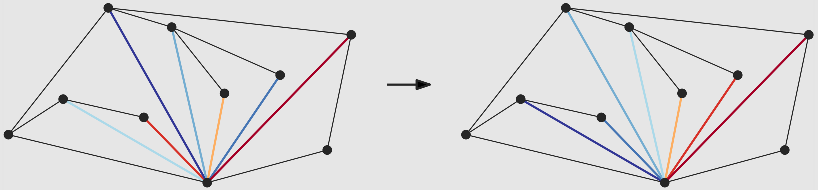
We can swap two consecutive bottom edges with $O(1)$ flips.

Tools

- *Sweep*: exchange labels on top and bottom pairs — $O(n)$



- *Shuffle*: reorder bottom labels — $O(n^2)$



Upper bound

Theorem

We can sort the labels of a left-shelling pseudo-triangulation with $O(1)$ shuffles and sweeps.

Theorem

We can transform any edge-labelled pointed pseudo-triangulation into any other with $O(n^2)$ flips.

Upper bound

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We can sort the labels of a left-shelling pseudo-triangulation with $O(1)$ shuffles and sweeps.

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- Can we do better?

Upper bound

Theorem

We can sort the labels of a left-shelling pseudo-triangulation with $O(1)$ shuffles and sweeps.

Theorem

We can transform any edge-labelled pointed pseudo-triangulation into any other with $O(n^2)$ flips.

- Can we do better? *I don't know.*

Lower bound

- Triangulation of convex polygon
  = pointed pseudo-triangulation

Theorem

The diameter of the flip graph is $\Omega(n \log n)$.

Open problems

- Close the $\Omega(n \log n)$–$O(n^2)$ gap for edge-labelled pointed pseudo-triangulations

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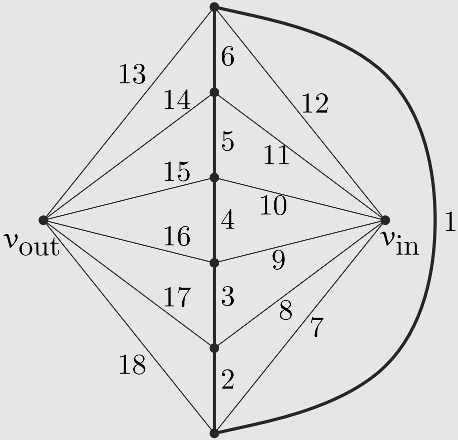
    - Variation: allow duplicate labels

Open problems

- Close the $\Omega(n \log n)$–$O(n^2)$ gap for edge-labelled pointed pseudo-triangulations
- Is it NP-hard to compute the flip distance between two edge-labelled triangulations?
  - Variation: allow duplicate labels
- Settle the *Orbit Conjecture* for triangulations of points in the plane
  - *e* “flips to” *f* if there is a triangulation where flipping e gives *f*
  - T_1 can be transformed into T_2 iff for all labels ℓ, the edge with label ℓ in T_1 flips to the edge with label ℓ in T_2
  - Clearly necessary. Sufficient?

Bonus: Combinatorial triangulations



Bonus: Combinatorial triangulations