VI. Approximation Algorithms: Travelling Salesman Problem

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UNIVERSITY OF CAMBRIDGE

Outline

Introduction

General TSP

Metric TSP

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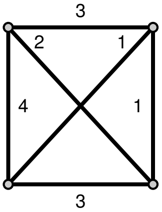

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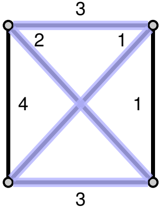

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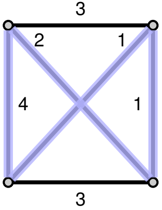

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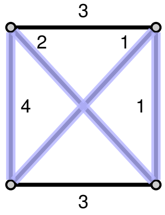

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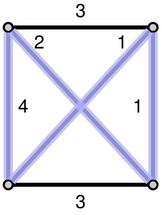

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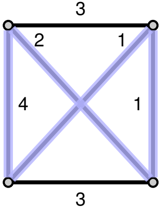

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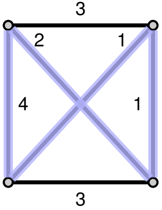

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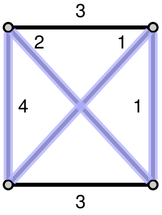

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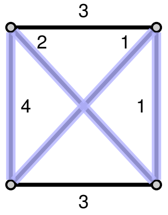

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Even this version is NP hard (Ex. 35.2-2)

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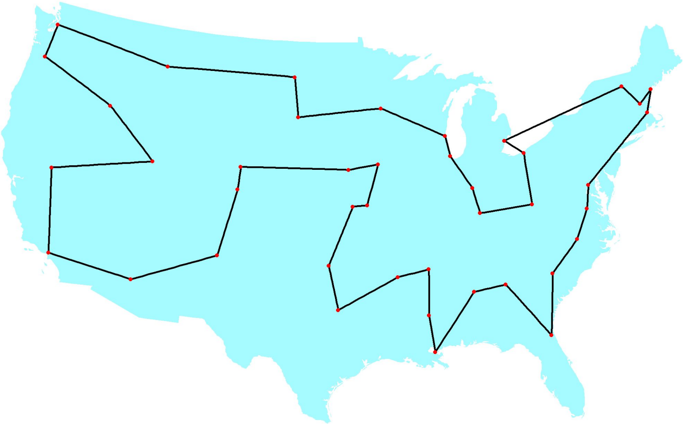
History of the TSP problem (1954)

Dantzig, Fulkerson and Johnson found an optimal tour through 42 cities.



`http://www.math.uwaterloo.ca/tsp/history/img/dantzig_big.html`

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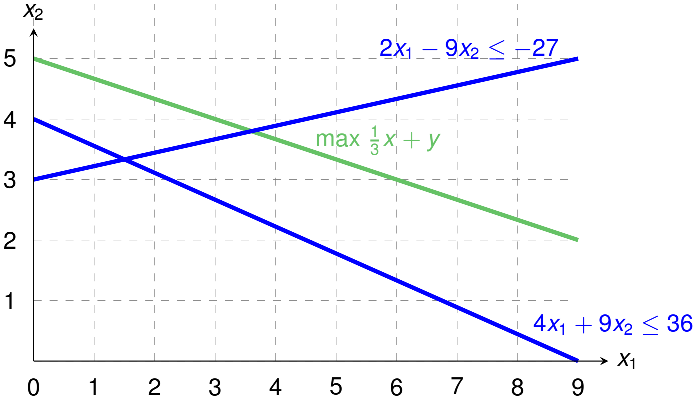

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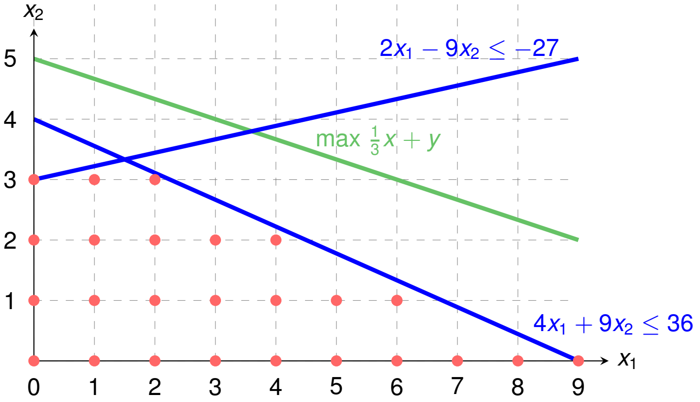

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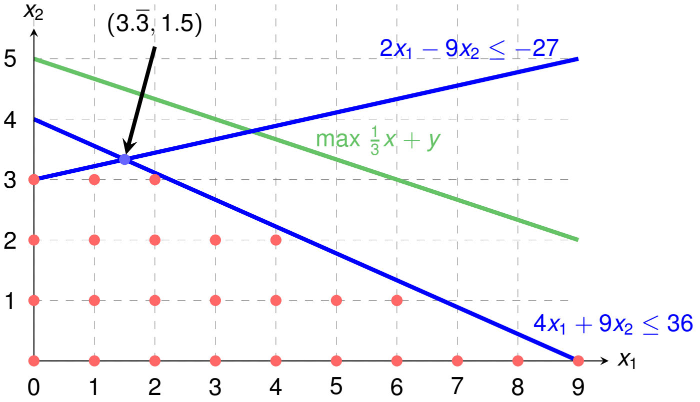

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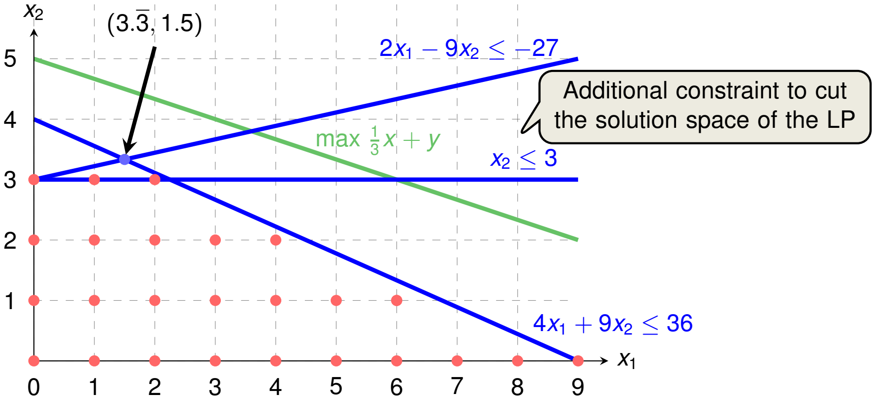

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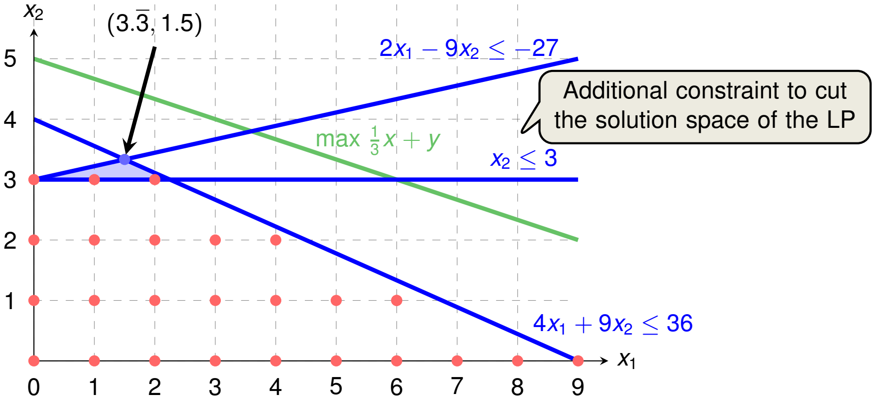

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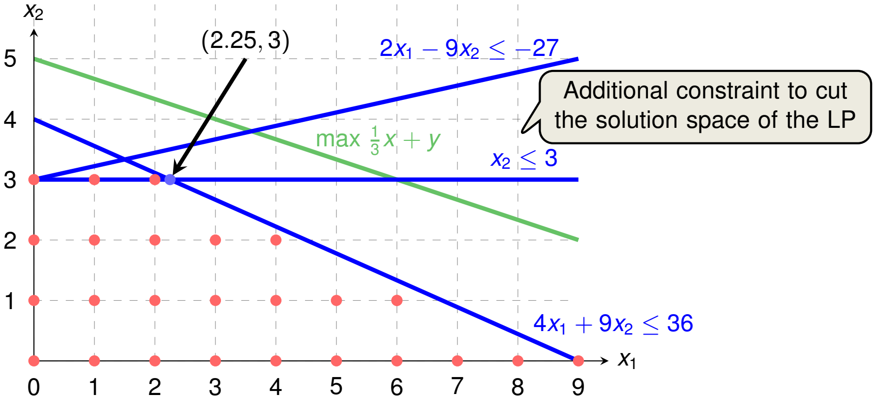

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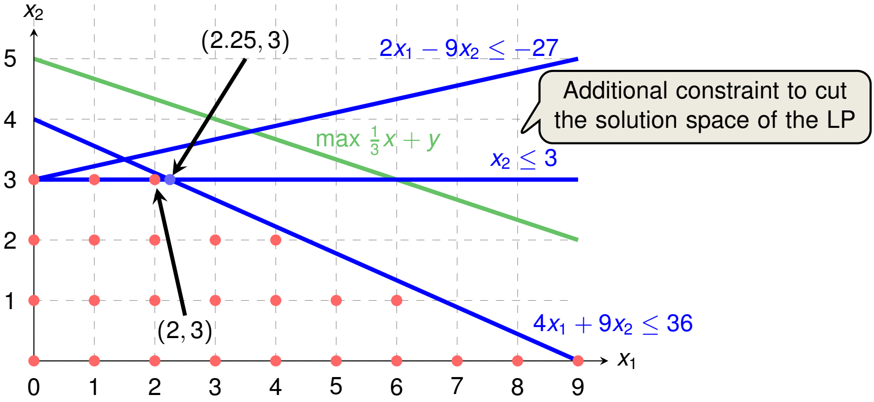

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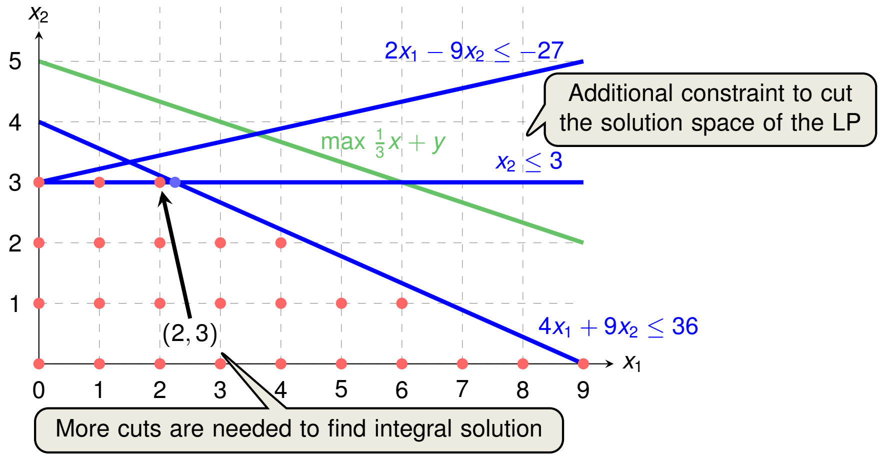

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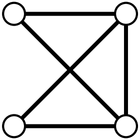

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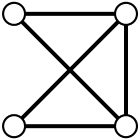

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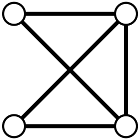

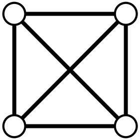

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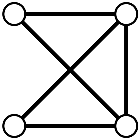

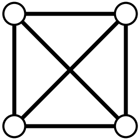

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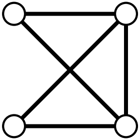

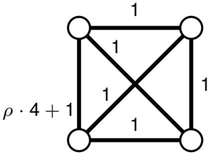

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Large weight will render this edge useless!

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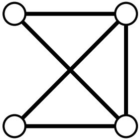

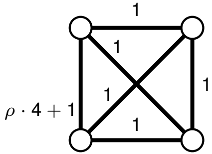

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Can create representations of G' and c in time polynomial in $|V|$ and $|E|$!

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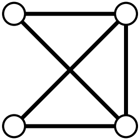
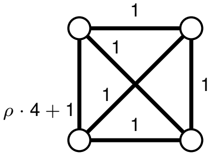
$G = (V, E)$ 



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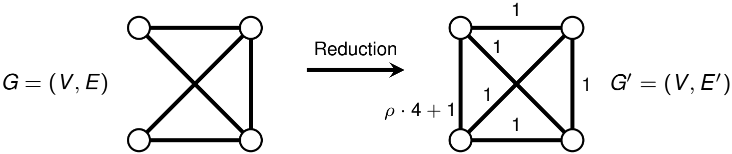

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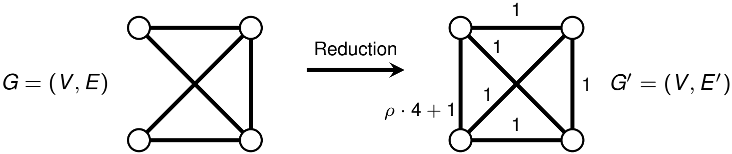

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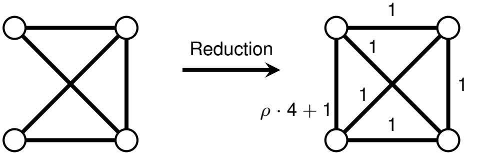

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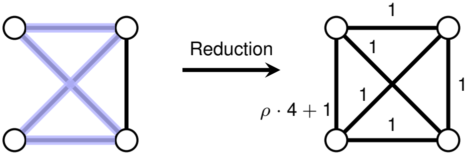

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Hardness of Approximation

Theorem 35.3

If P $\neq$ NP, then for any constant $\rho \geq 1$, there is no polynomial-time approximation algorithm with approximation ratio ρ for the general TSP.

Proof: Idea: Reduction from the hamiltonian-cycle problem.

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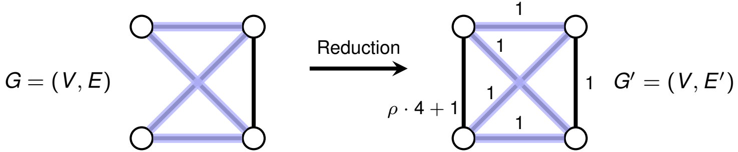

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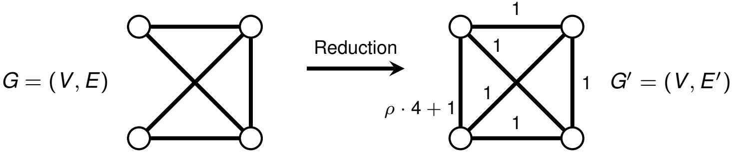

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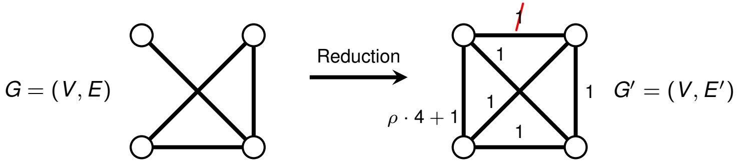

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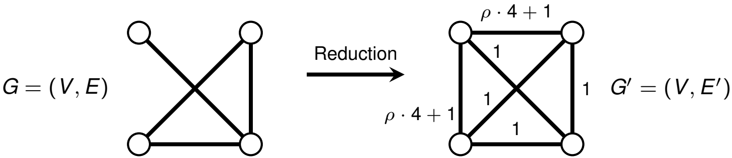

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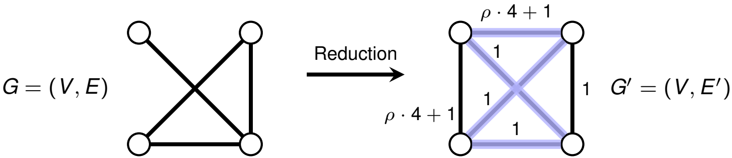

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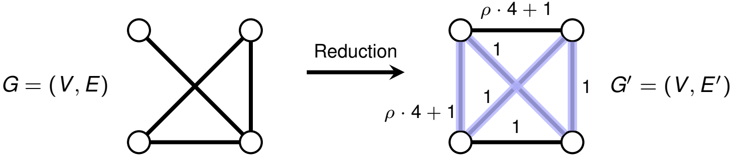

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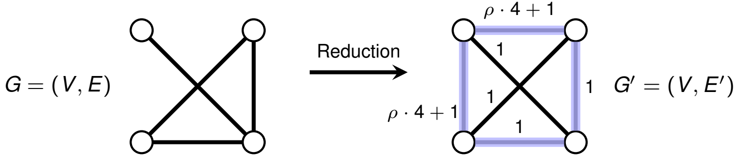

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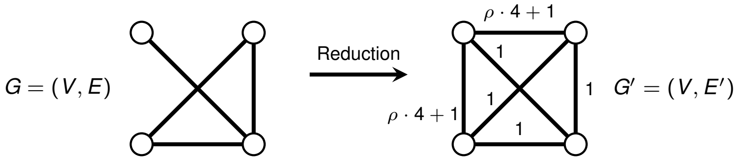

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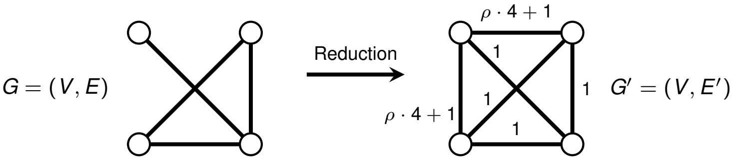

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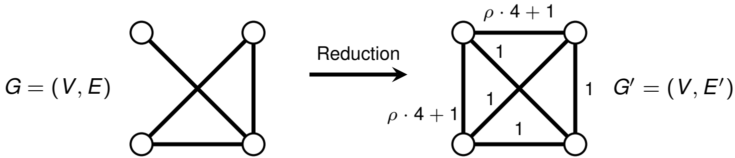

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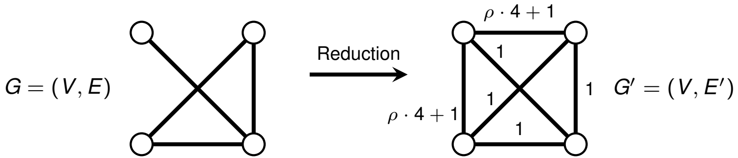

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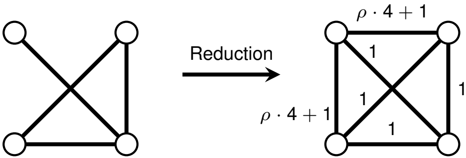

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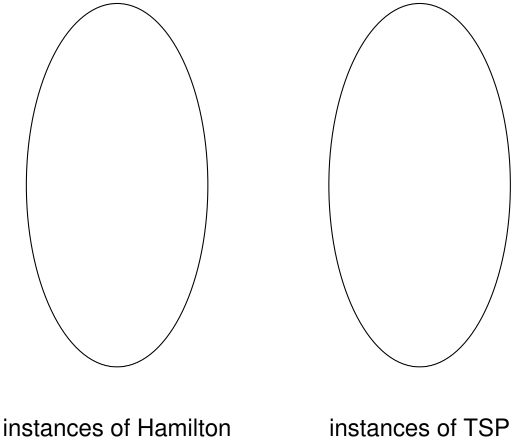
Proof of Theorem 35.3 from a higher perspective



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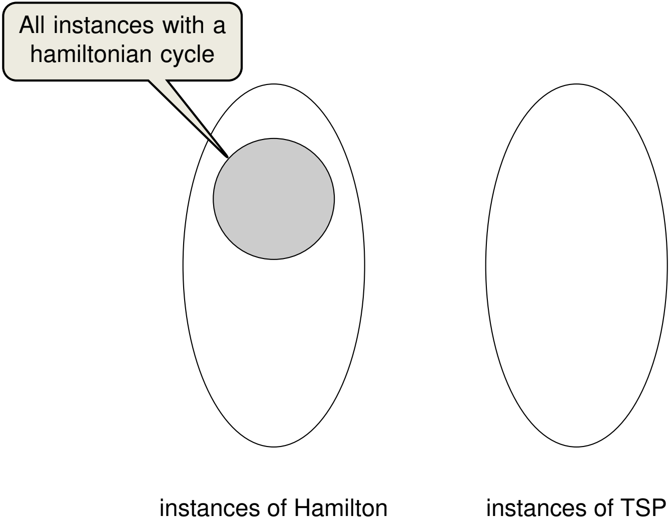

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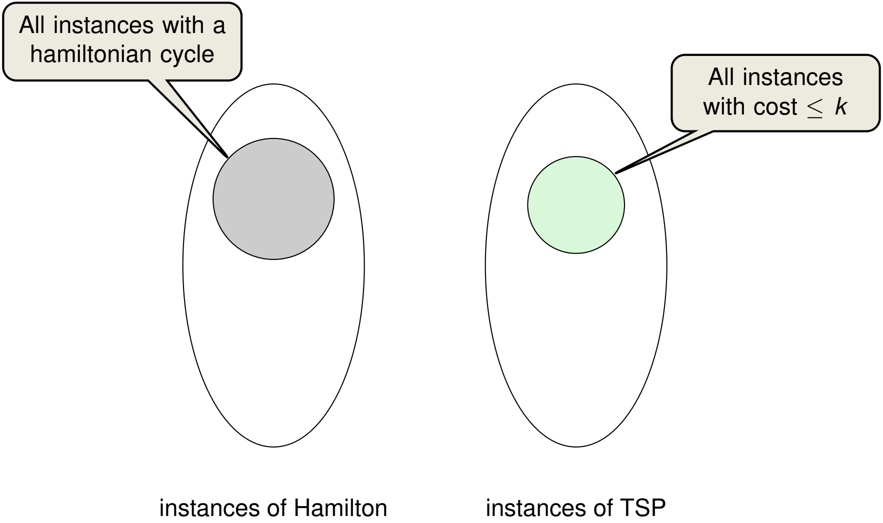

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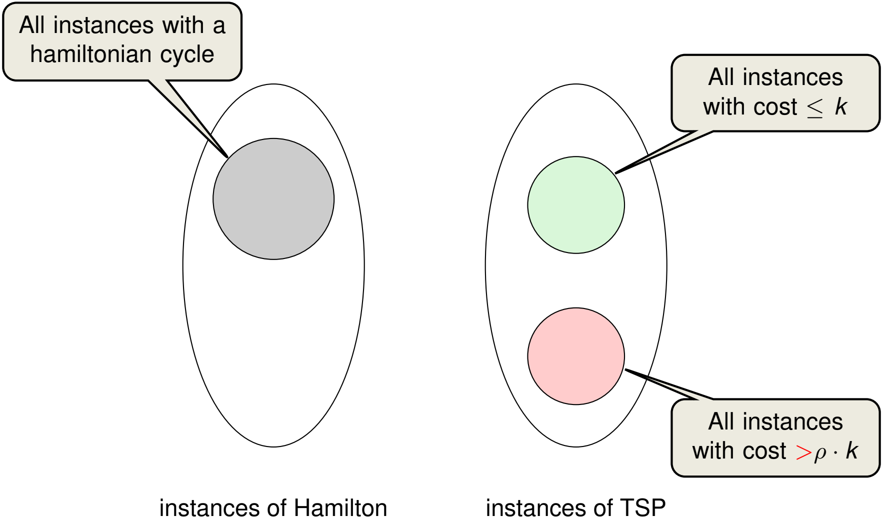

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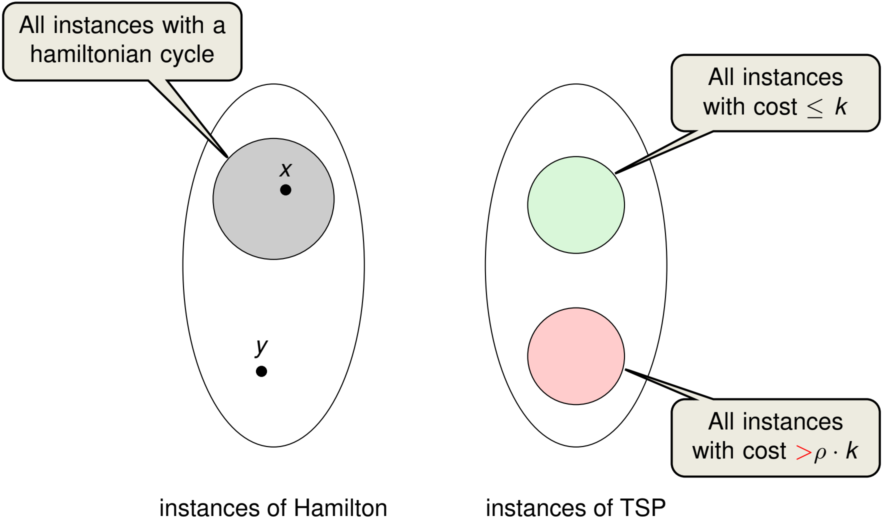

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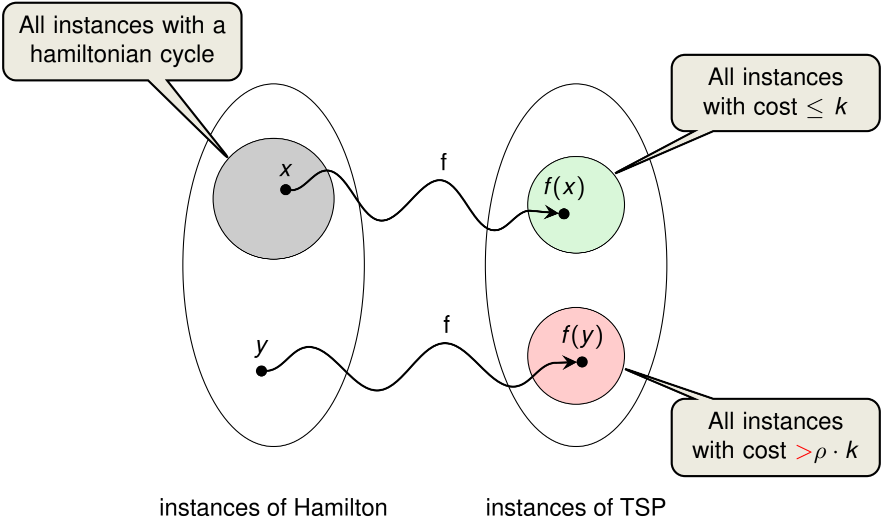

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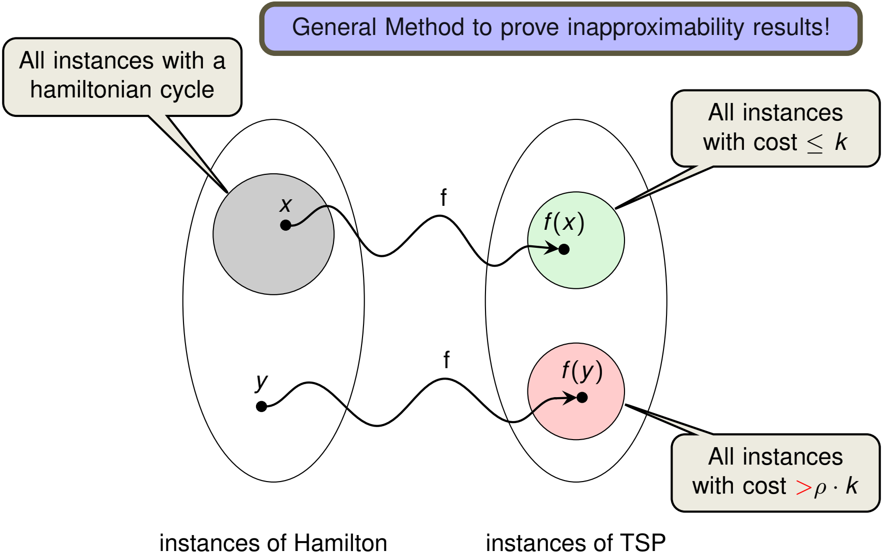

Outline

Introduction

General TSP

Metric TSP

Metric TSP (TSP Problem with the Triangle Inequality)

Idea: First compute an MST, and then create a tour based on the tree.

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APPROX-TSP-TOUR(G, c)
select a vertex r ∈ G.V to be a "root" vertex
compute a minimum spanning tree T for G from root r
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return the hamiltonian cycle H
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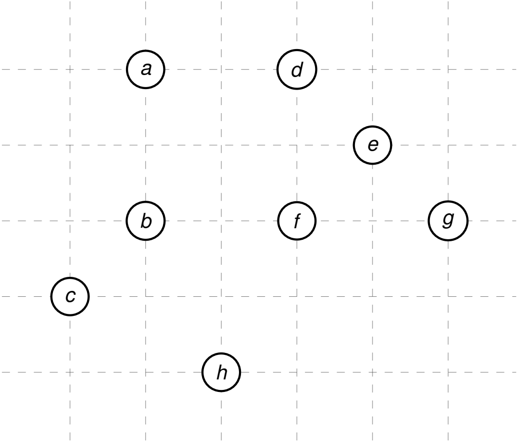
Remember: In the Metric-TSP problem, G is a complete graph.

Run of APPROX-TSP-TOUR



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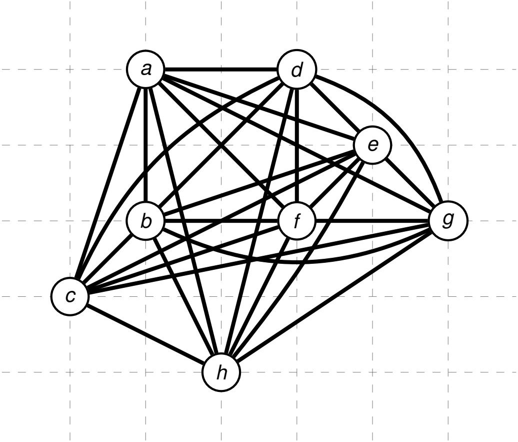

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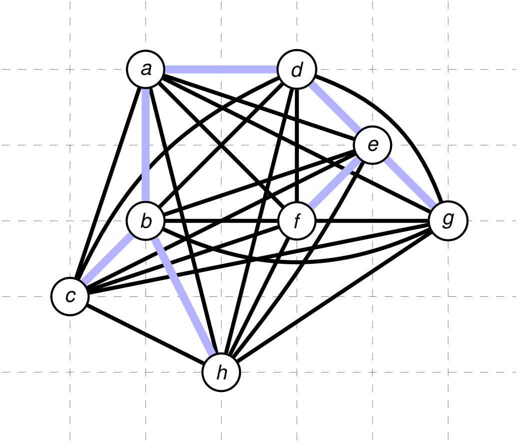
Run of APPROX-TSP-TOUR



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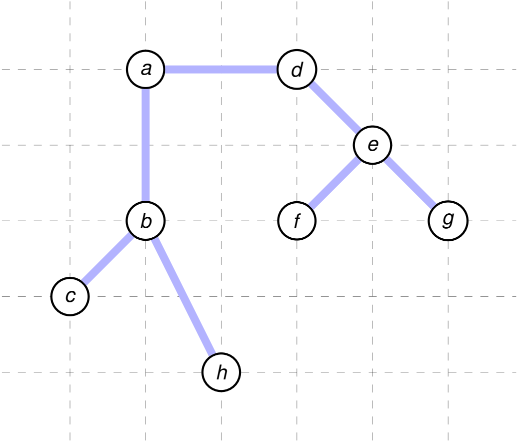

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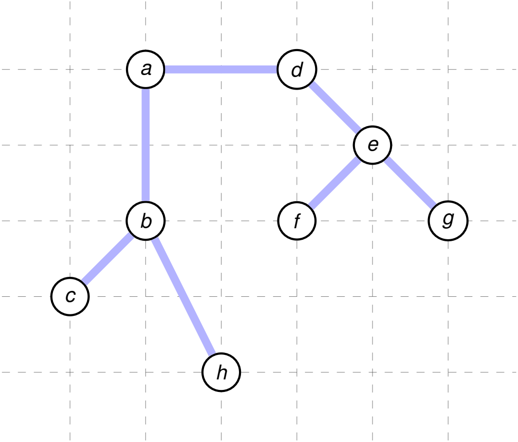

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2. Perform preorder walk on MST

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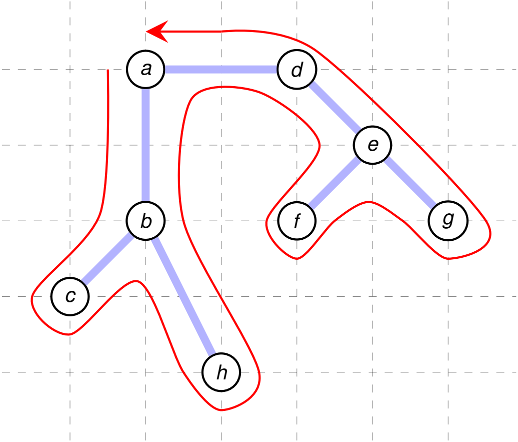

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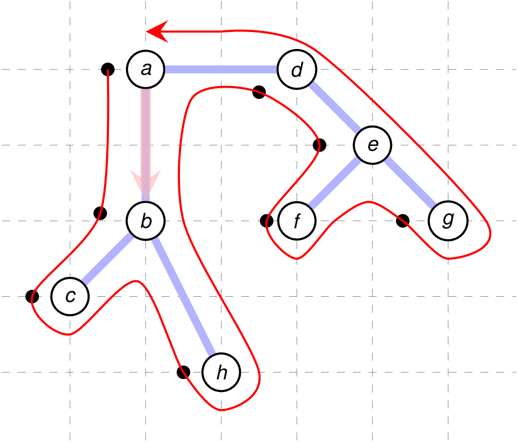

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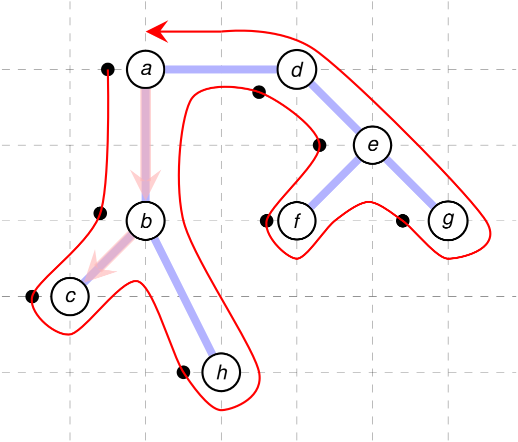

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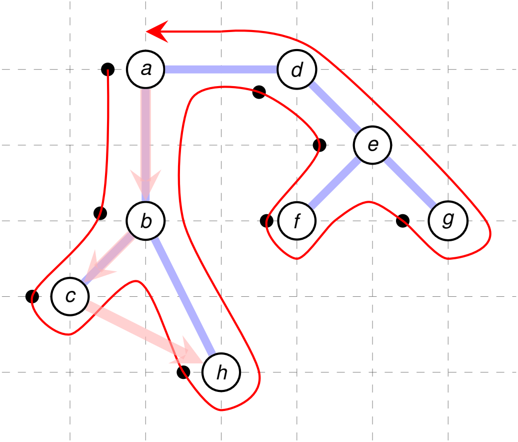

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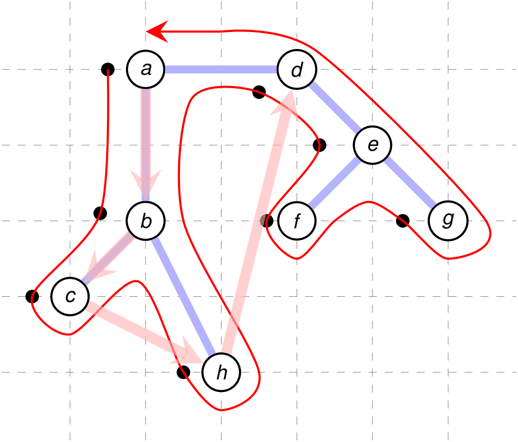

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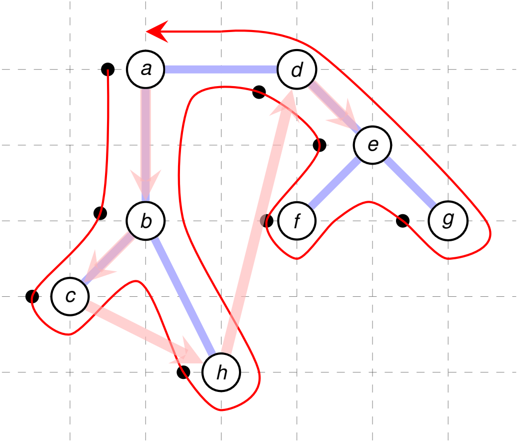

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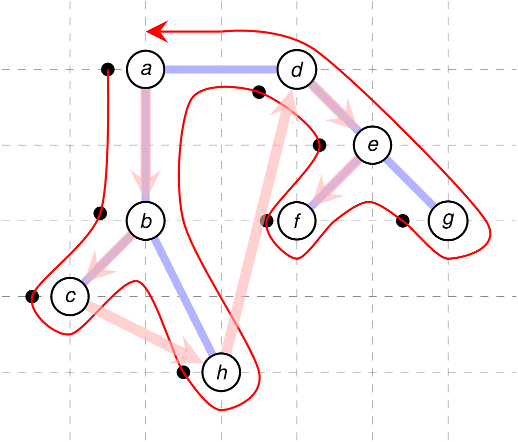

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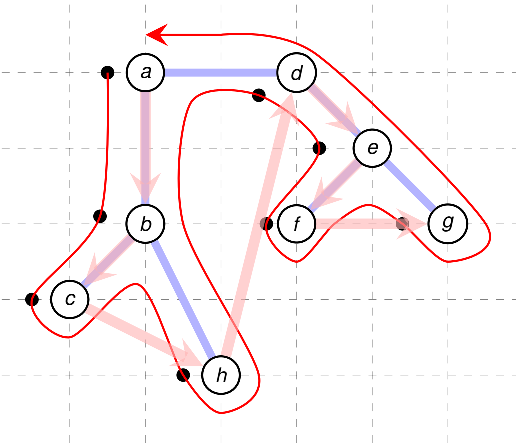

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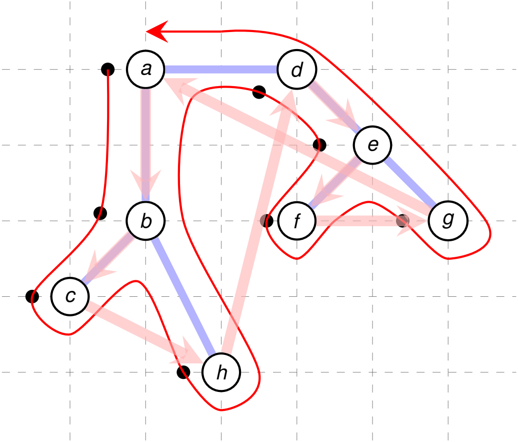

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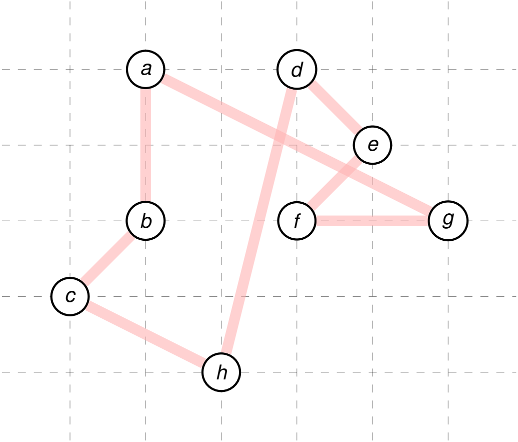

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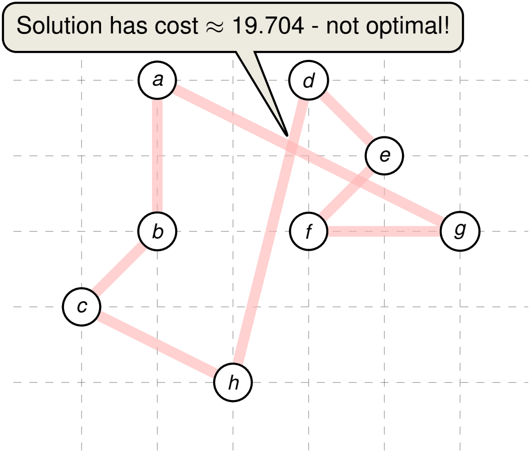

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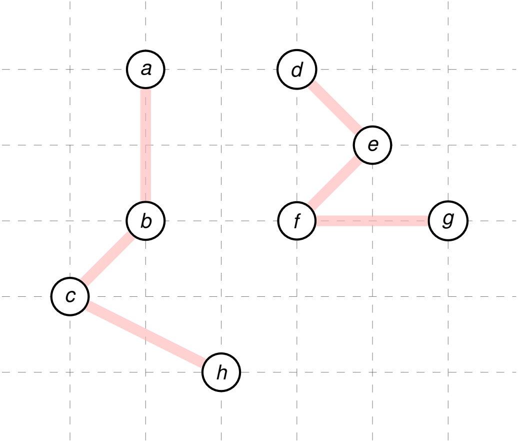
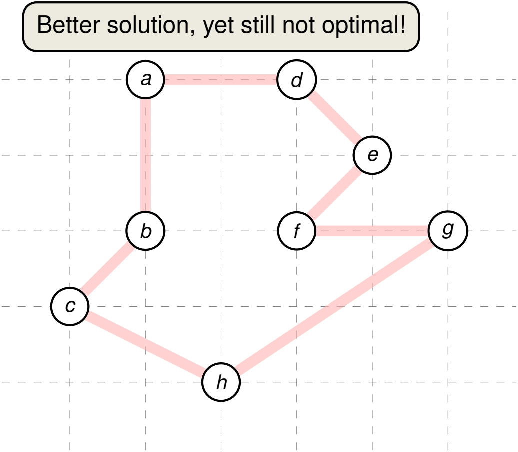


1. Compute MST ✓
2. Perform preorder walk on MST ✓
3. Return list of vertices according to the preorder tree walk ✓

Run of APPROX-TSP-TOUR



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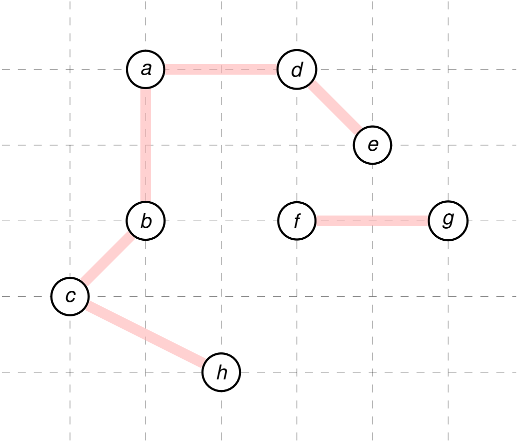

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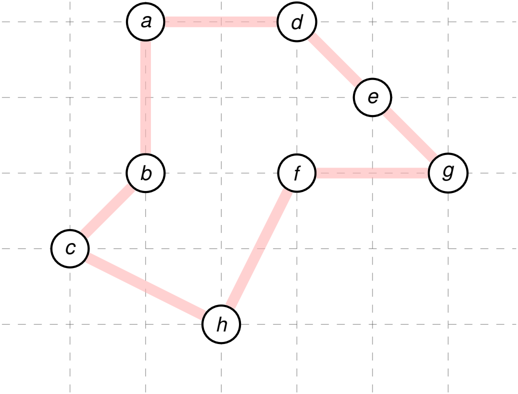
Run of APPROX-TSP-TOUR

This is the optimal solution (cost $\approx$ 14.715).



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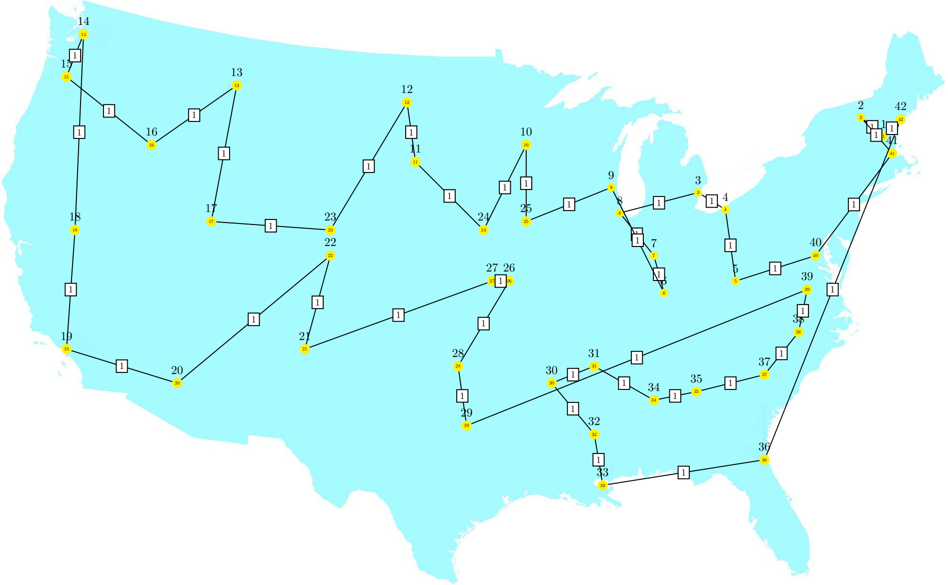
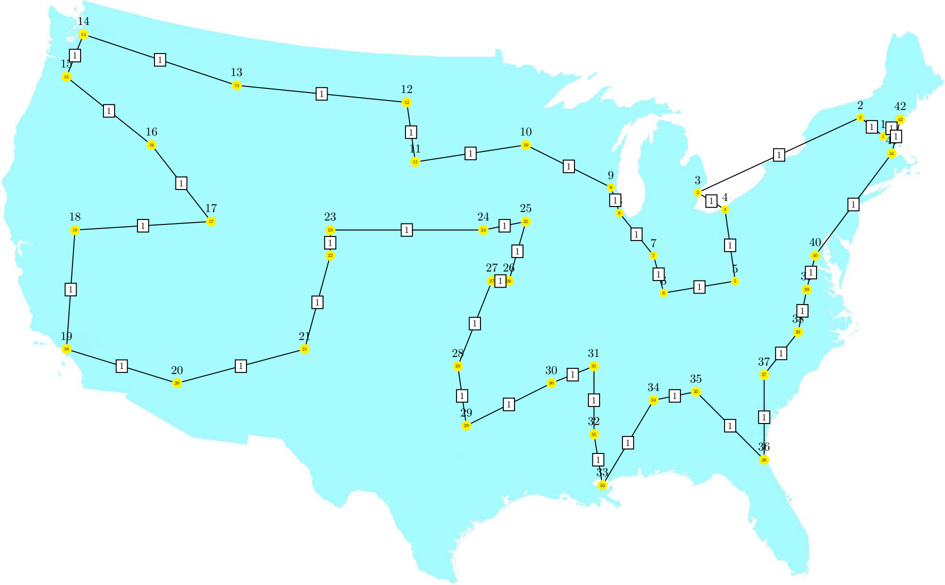
Approximate Solution: Objective 921



Optimal Solution: Objective 699



Proof of the Approximation Ratio

Theorem 35.2

APPROX-TSP-TOUR is a polynomial-time 2-approximation for the traveling-salesman problem with the triangle inequality.

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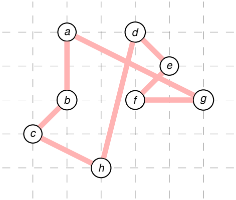

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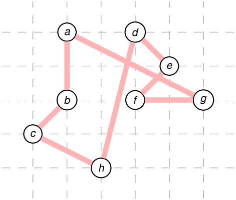

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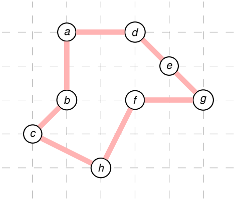

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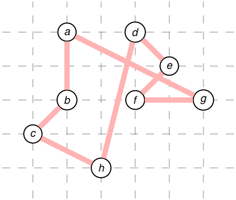

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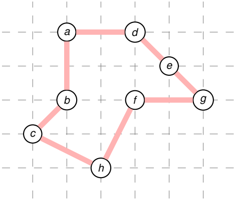

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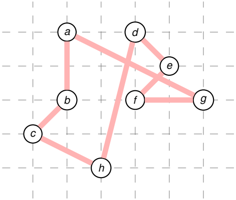

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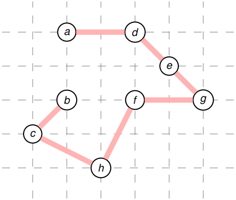

spanning tree T as a subset of H^*

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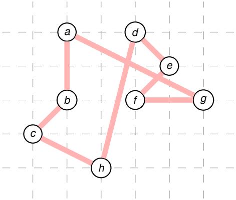

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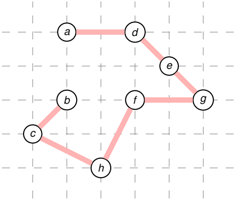

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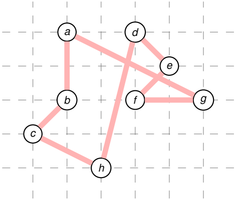

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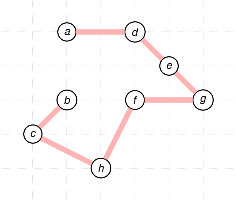

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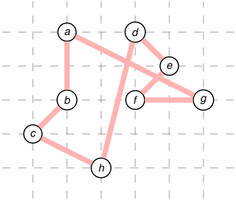
exploiting that all edge costs are non-negative!



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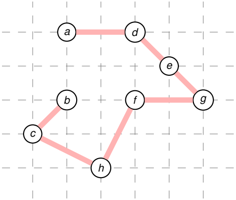

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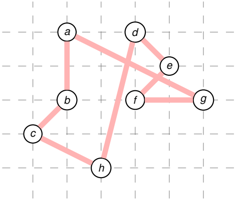

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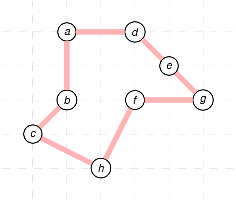

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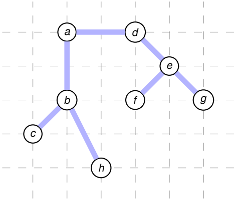
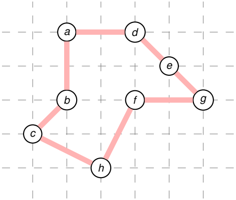


minimum spanning tree T_{min}



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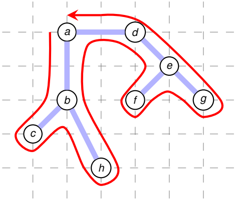
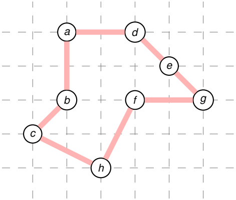


Walk $W = (a, b, c, b, h, b, a, d, e, f, e, g, e, d, a)$



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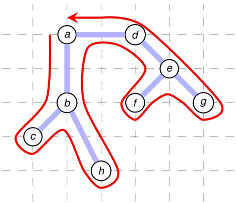

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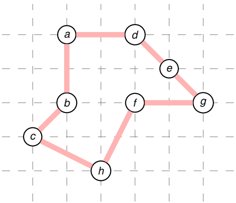

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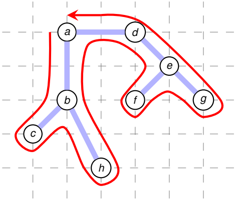

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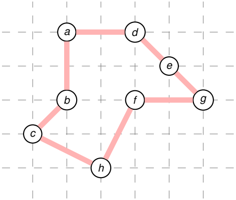

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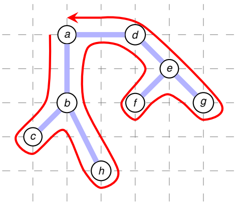

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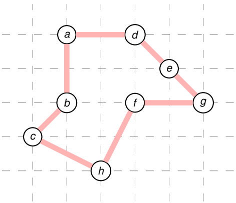

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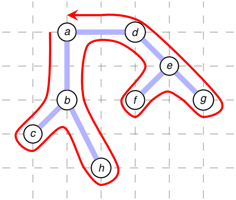

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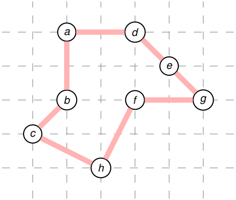

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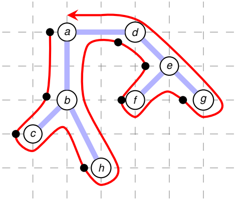

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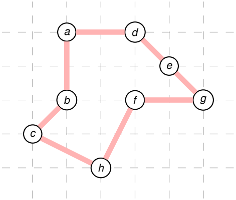

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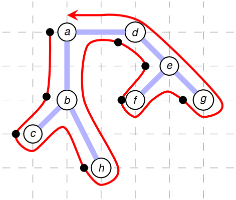

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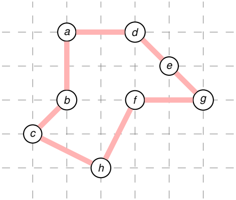

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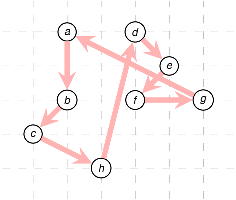
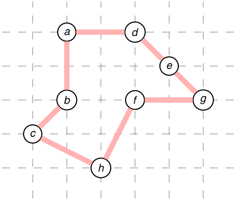


Tour $H = (a, b, c, h, d, e, f, g, a)$



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exploiting triangle inequality!

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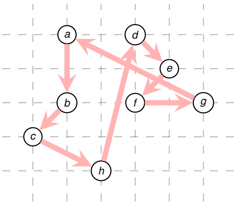

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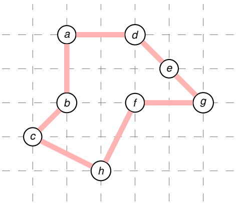

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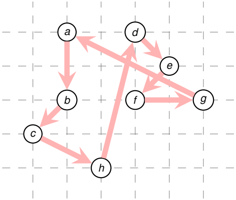

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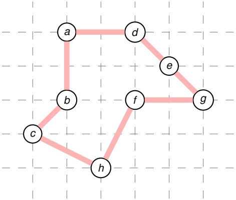

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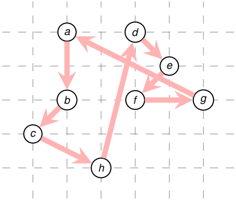

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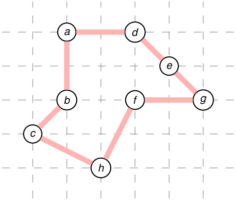


optimal solution H^*

Proof of the Approximation Ratio

Theorem 35.2

APPROX-TSP-TOUR is a polynomial-time 2-approximation for the traveling-salesman problem with the triangle inequality.

Proof:

- Consider the optimal tour H^* and remove an arbitrary edge

$\Rightarrow$ yields a spanning tree T and ~~therefore~~ $c(T) \leq c(H^*)$

- Let W be the full walk of the minimum spanning tree T_{min} (including repeated visits)

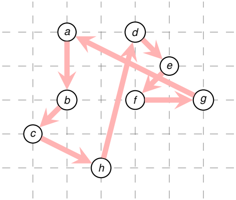
$\Rightarrow$ Full walk traverses every edge exactly twice, so

$$c(W) = 2c(T_{\text{min}}) \leq 2c(T) \leq 2c(H^*)$$

exploiting triangle inequality!

- Deleting duplicate vertices from W yields a tour H with smaller cost:

$$c(H) \leq c(W) \leq 2c(H^*)$$



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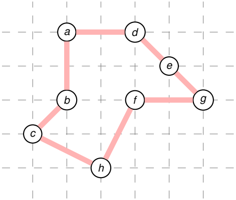

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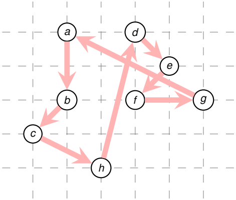

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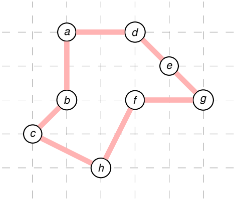

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Christofides Algorithm

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Can we get a better approximation ratio?

Christofides Algorithm

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Can we get a better approximation ratio?

CHRISTOFIDES(G, c)
select a vertex $r \in G.V$ to be a "root" vertex
compute a minimum spanning tree T for G from root r
    using MST-PRIM(G, c, r)
compute a perfect matching M with minimum weight in the complete graph
    over the odd-degree vertices in T
let H be a list of vertices, ordered according to when they are first visited
    in a Eulearian circuit of $T \cup M$
return H

Christofides Algorithm

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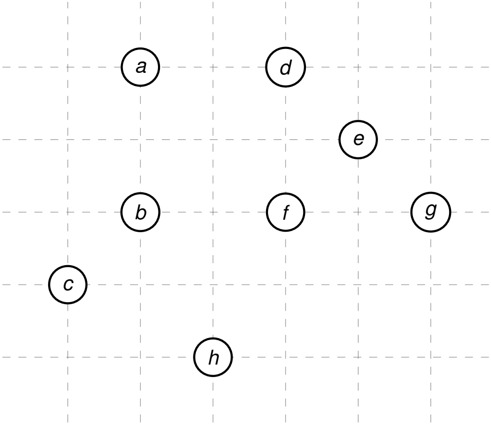
Theorem (Christofides'76)

There is a polynomial-time $\frac{3}{2}$-approximation algorithm for the travelling salesman problem with the triangle inequality.

Run of CHRISTOFIDES



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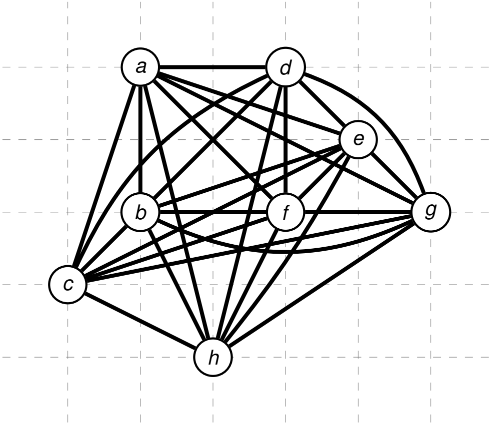
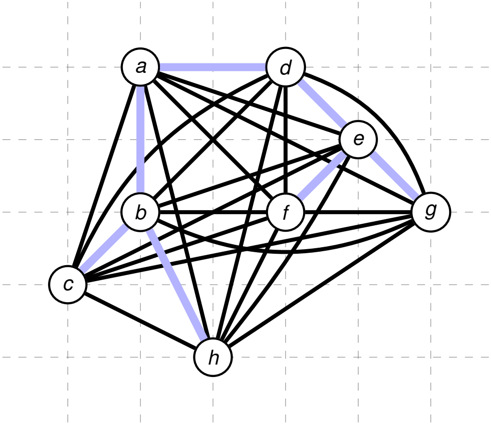


1. Compute MST

Run of CHRISTOFIDES



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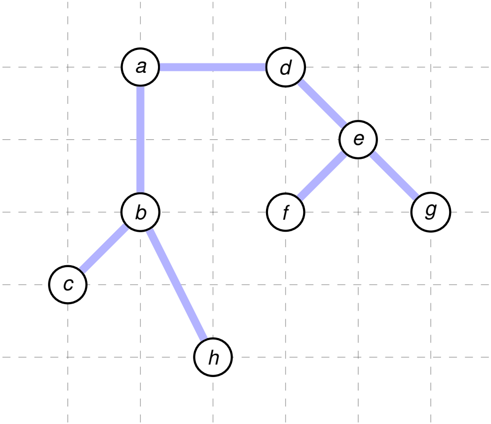

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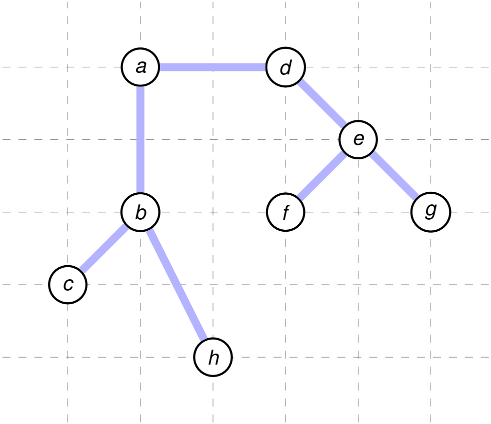
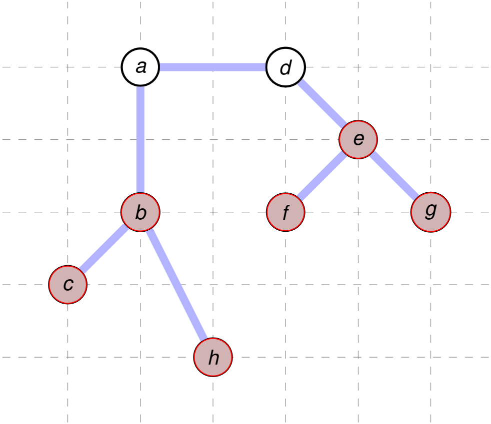
Run of CHRISTOFIDES



1. Compute MST ✓
2. Add a minimum-weight perfect matching M of the odd vertices in T

Run of CHRISTOFIDES



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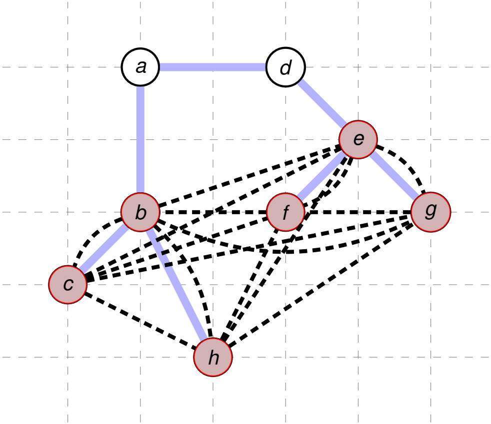

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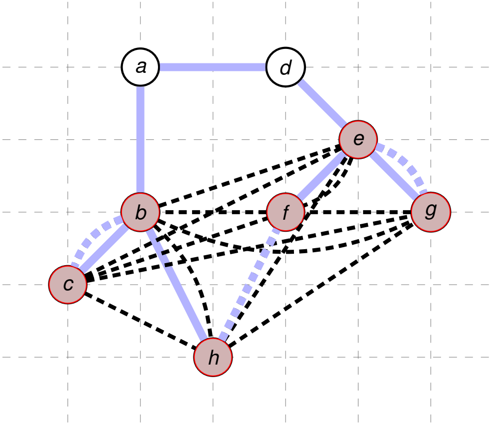

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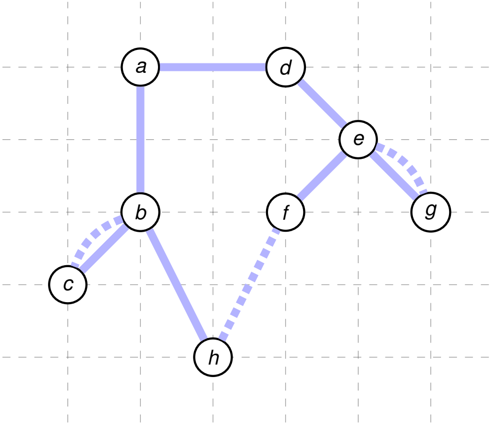

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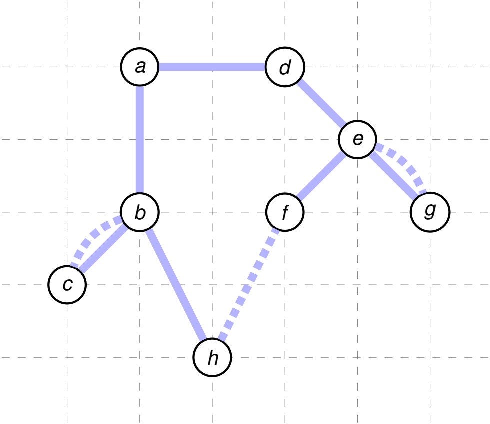

1. Compute MST ✓
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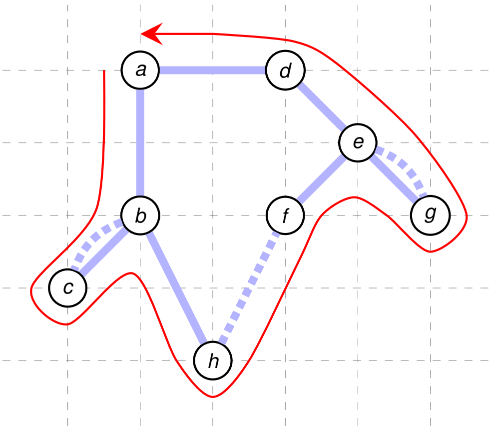
3. Find an Eulerian Circuit

All vertices in $T \cup M$ have even degree!

Run of CHRISTOFIDES



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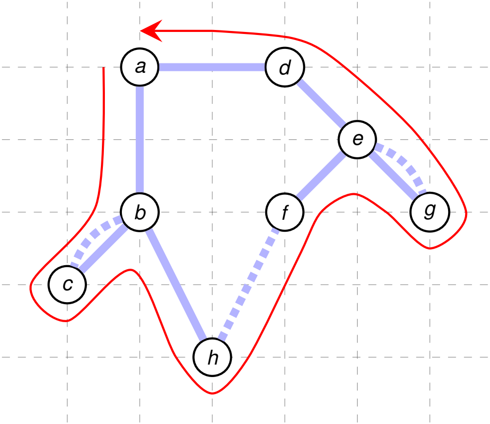

1. Compute MST ✓
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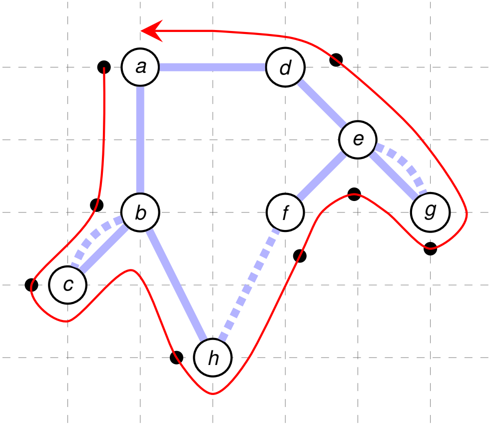
3. Find an Eulerian Circuit ✓
4. Transform the Circuit into a Hamiltonian Cycle

Run of CHRISTOFIDES



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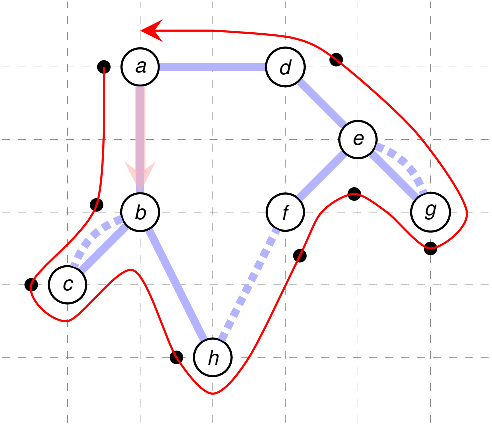

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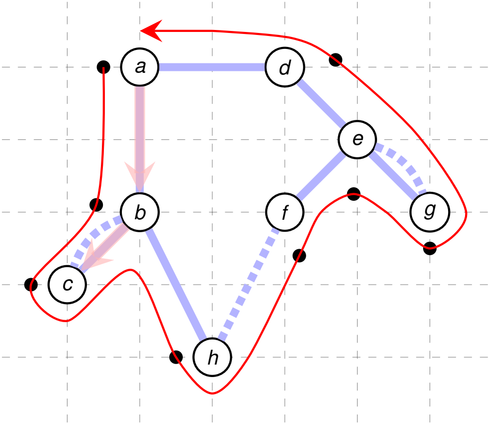

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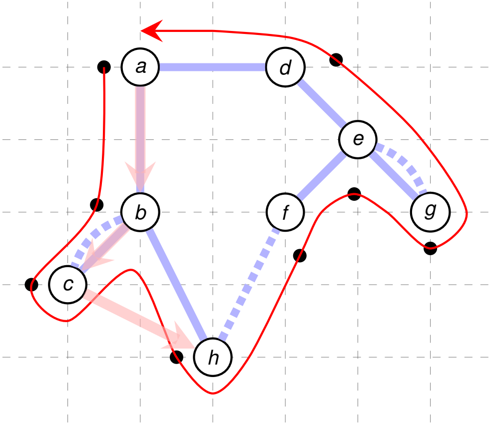

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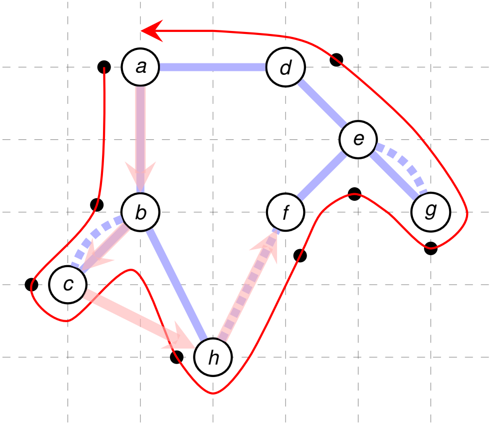

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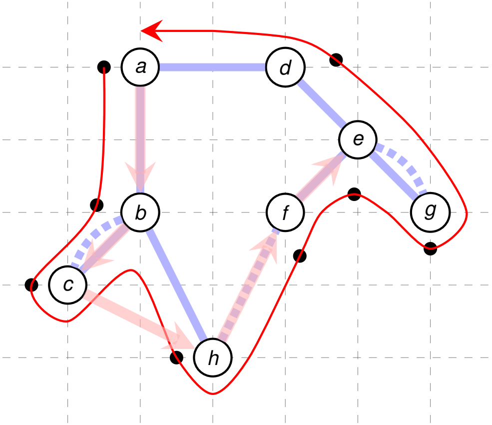

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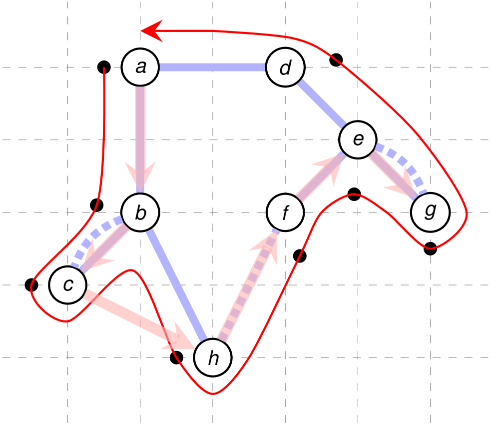

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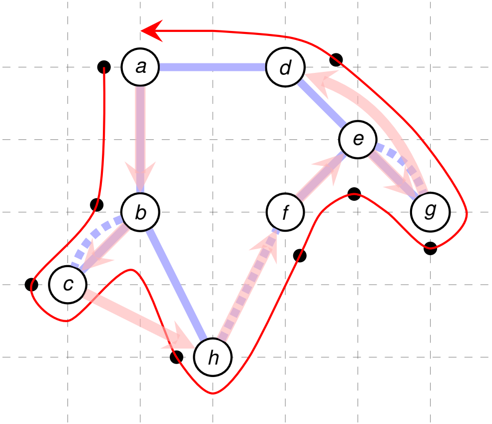

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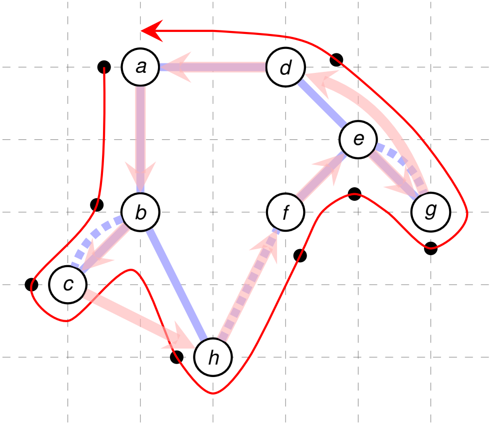

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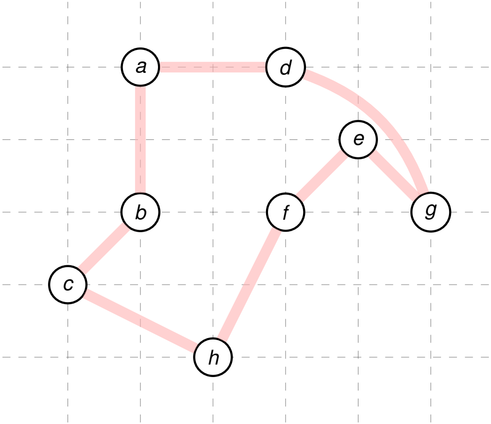

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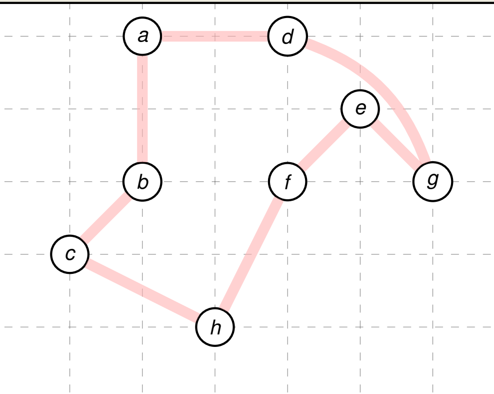
Solution has cost ≈ 15.54 - within 10% of the optimum!



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Concluding Remarks

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