ETH zürich

Energy-efficient Delivery by Heterogeneous Mobile Agents

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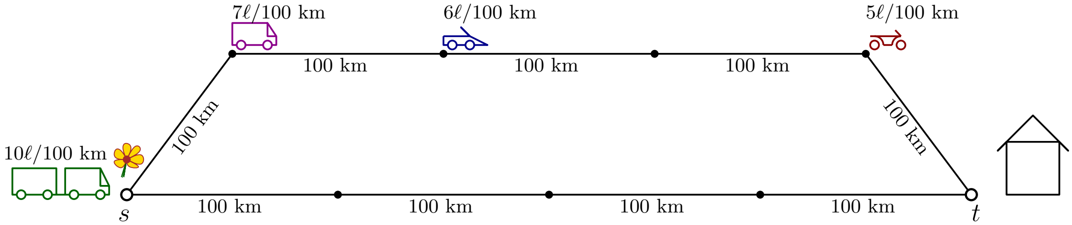
Motivation / Toy model



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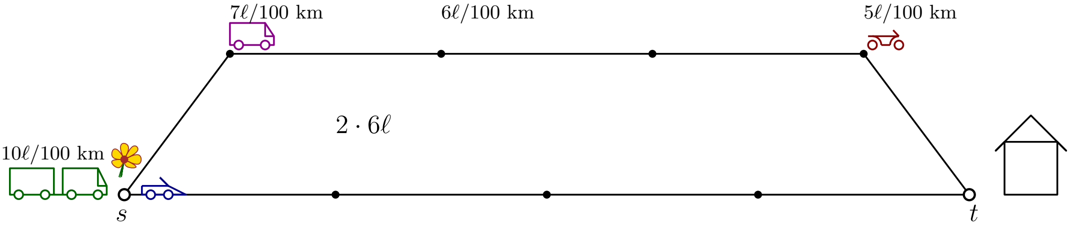

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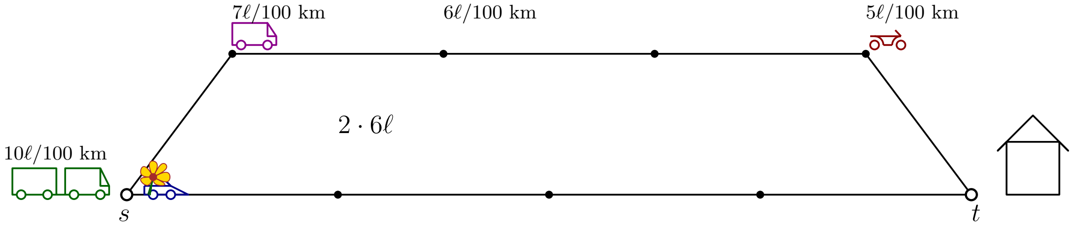

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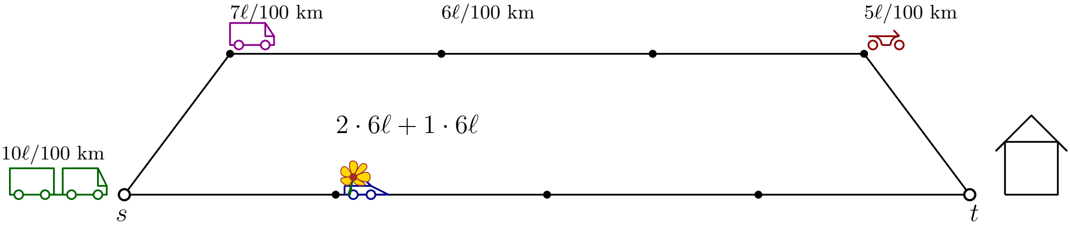

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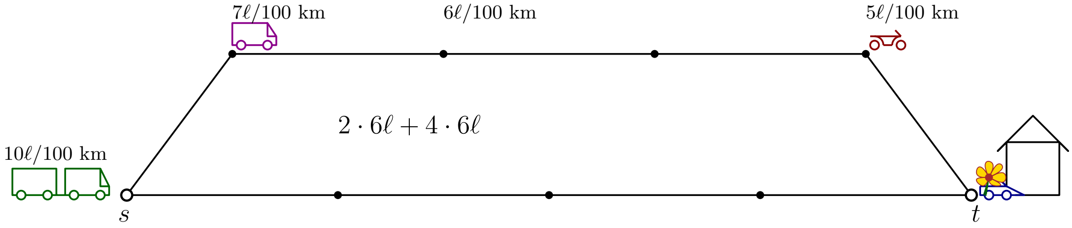

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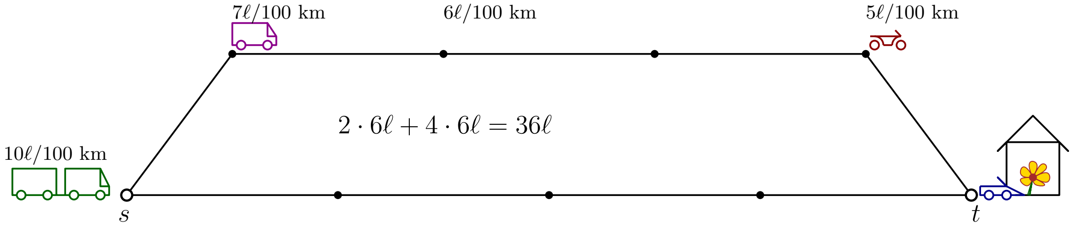

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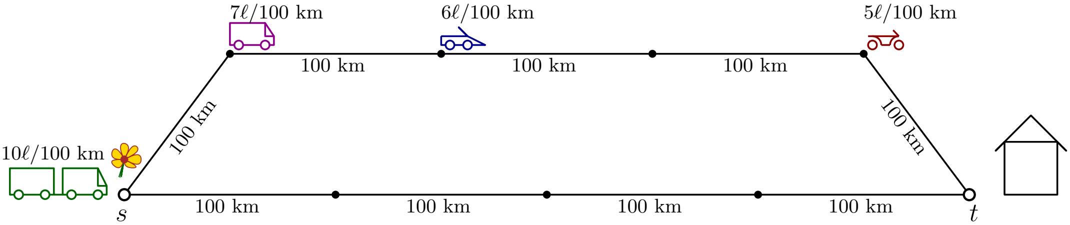

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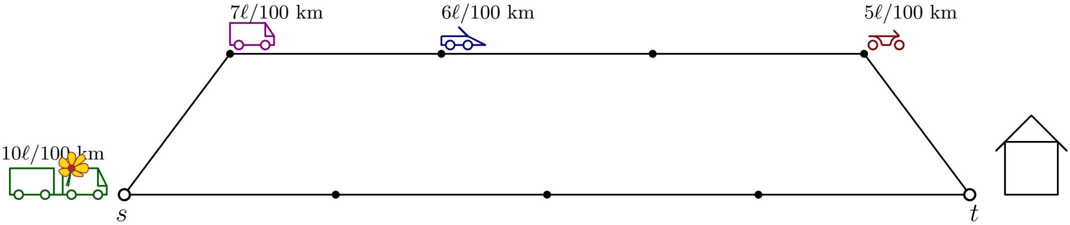

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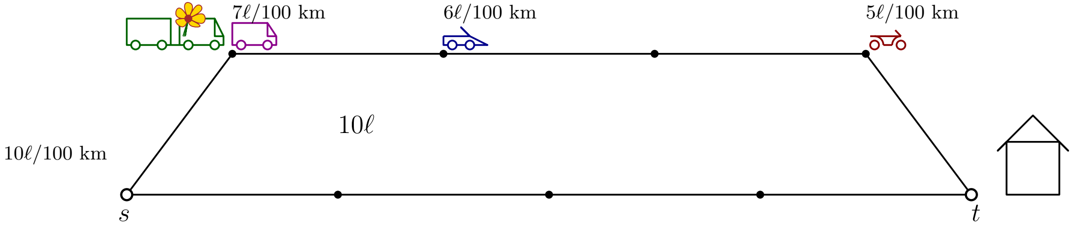

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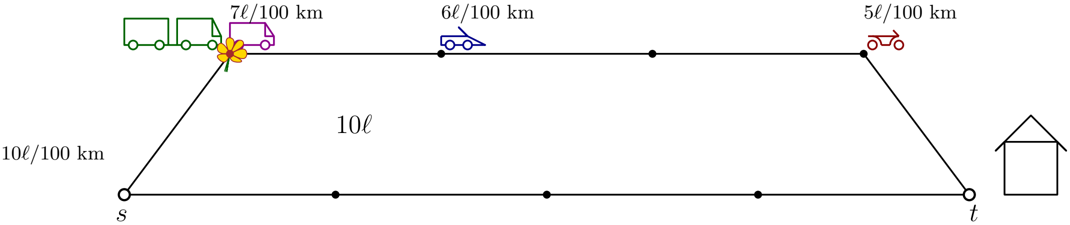

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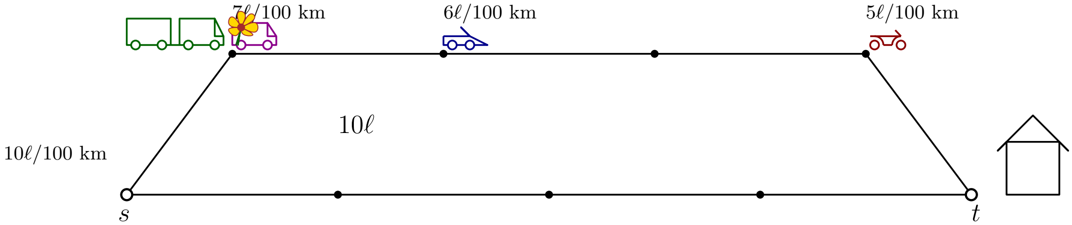

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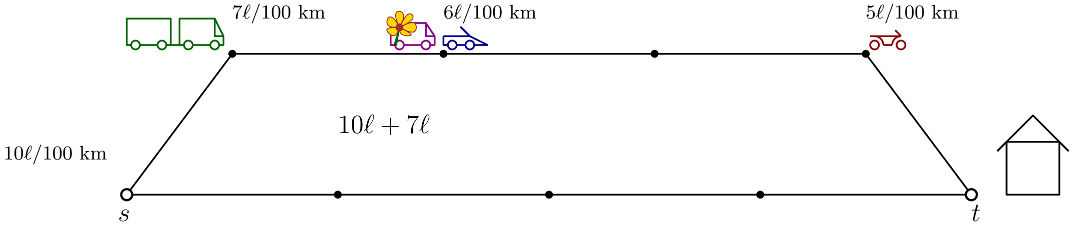

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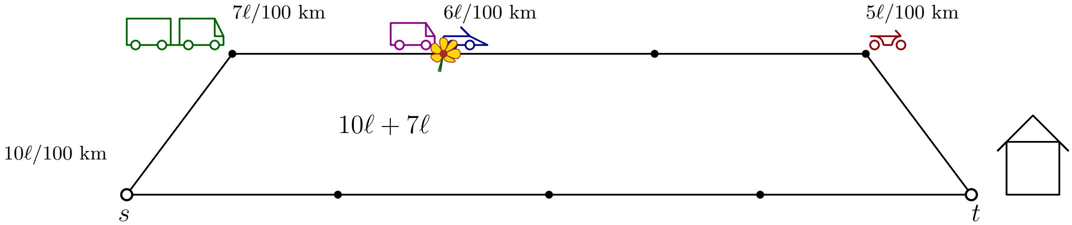

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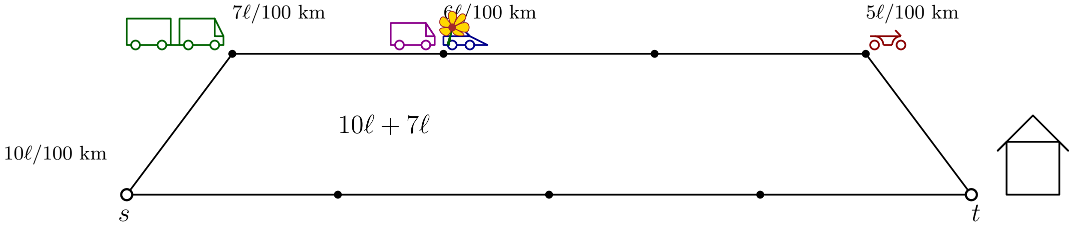

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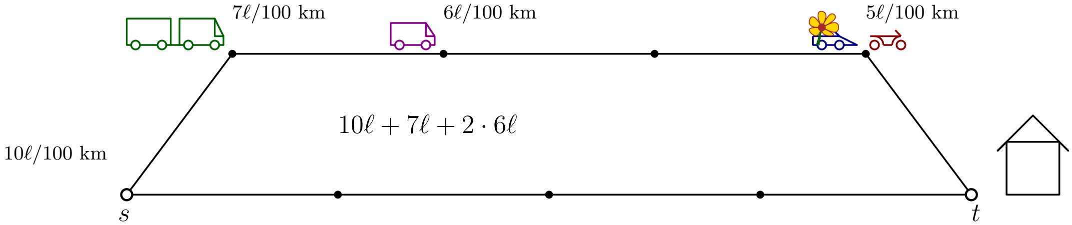

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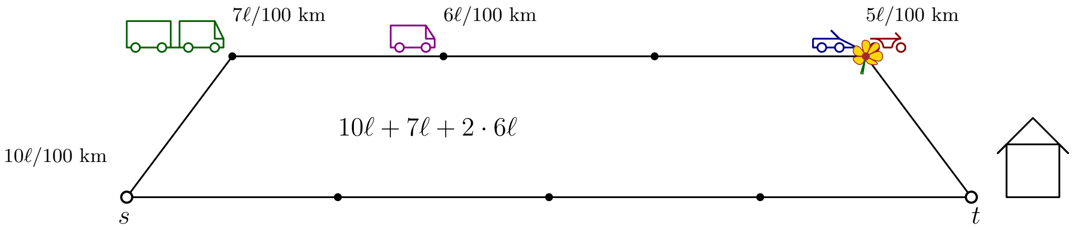

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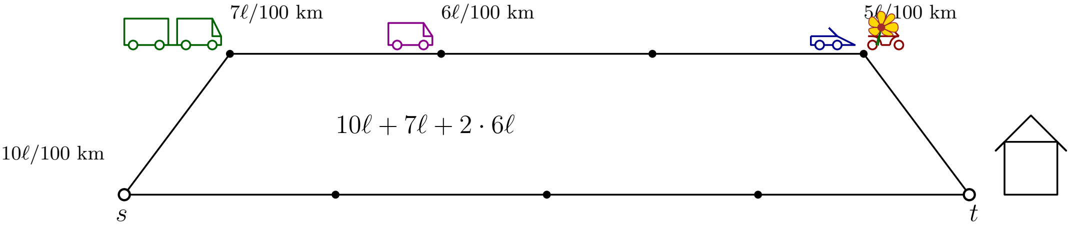

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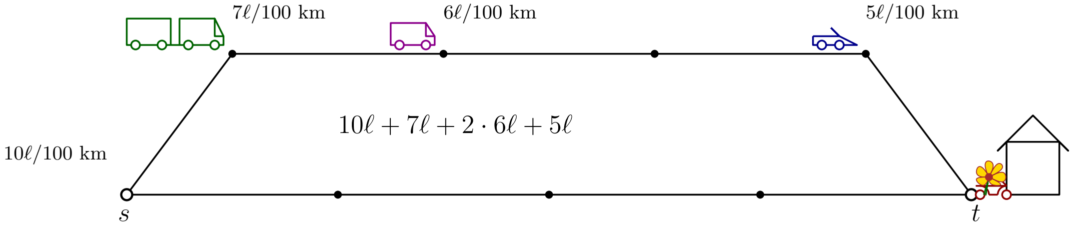

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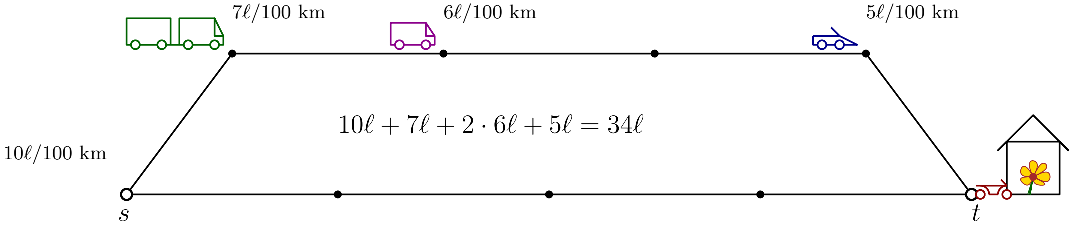

$$10\ell + 7\ell + 2 \cdot 6\ell + 5\ell = 34\ell$$

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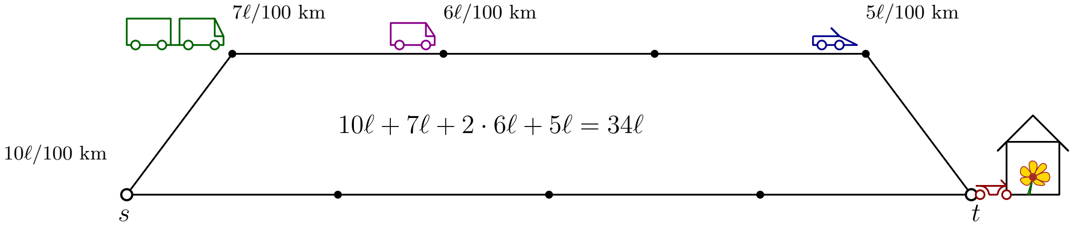

We extend this with:

- multiple items to be delivered (*messages*)
- varying road lengths (*edge lengths*)
- many vehicles (*mobile agents*)
- handovers at cities (*nodes*)

Model

Setting

- undirected graph $G = (V, E)$ with edges E having lengths
- m messages, given by source-target node pairs (s_i, t_i)
- anyone can use any edge

Agents

- k agents each with capacity κ and
  - starting position $p_i \in V$
  - rate of energy consumption w_i also called **weights**

Assumptions

- global coordination
- handovers possible at nodes V

Task

Find a delivery schedule which minimizes overall energy cost, given by the weighted sum of each agent's travel distance d_i:

$$\sum_{i=1}^{k} w_i \cdot d_i$$

Collaboration, Planning and Coordination

Collaboration

How should the agents work together on each message?

Planning

Which route should each agent take?

Coordination

How should the agents be assigned to the messages?

Collaboration, Planning and Coordination

Collaboration

How should the agents work together on each message?

- Defines all handover points of a message and their order.
- An agent then carries it between consecutive handover points.

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- Assigns a subset of the messages to each agent.
- Depends on the starting position of an agent, and on its weight.

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} simultaneously + more details!

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- Defines all handover points of a message and their order.
- An agent then carries it between consecutive handover points.

→ This includes the case of a *single message*.

Planning

Which route should each agent take?

- Gives an order of all pick-ups and all drop-offs of each agent.

→ This includes the case of a *single agent*.

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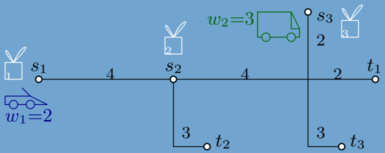
+ more details!

How should the agents work together on each message?

$m = 1$: Agent weights are decreasing $\rightarrow$ dynamic programming

How should the agents work together on each message?

$m > 1$: No characterization.



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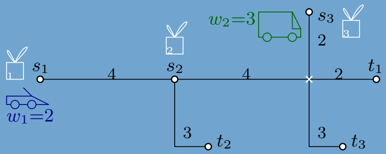

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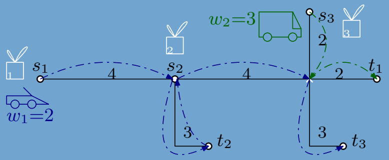

energy cost

$$= 2 \cdot (4 + 3 + 3 + 4 + 3) + 3 \cdot (2 + 2) = 46$$

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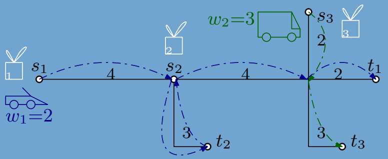

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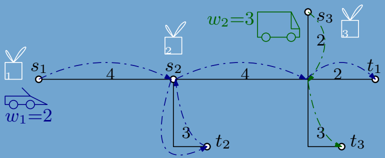

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How far off is a schedule in which agents do not collaborate?

Theorem (Benefit of Collaboration BoC)

The benefit of collaboration is at most 2.

Proof Idea: Build non-collaborative solution from an arbitrary optimum (with collaboration).

1. Trajectory graph + backward edges
2. Generalization of Euler tours

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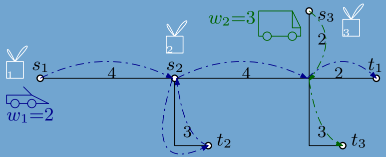

energy cost
$= 2 \cdot (4+3+3+4+2)$
$+ 3 \cdot (2+3) = 47$

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For $\underline{\kappa = 1}$, this holds even if in the non-collaboration scenario
(i) messages are directly delivered, and
(ii) agents return to their starting position in the end.

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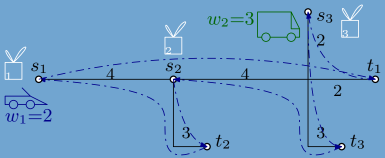

energy cost
$= 2 \cdot 2 \cdot (4 + 3 + 4 + 2 + 2 + 3)$
$= 72$

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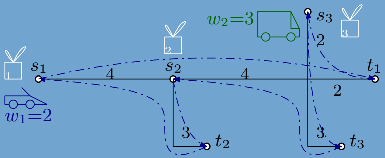

$\underline{\kappa = 1}$: no collaboration + direct delivery + return:

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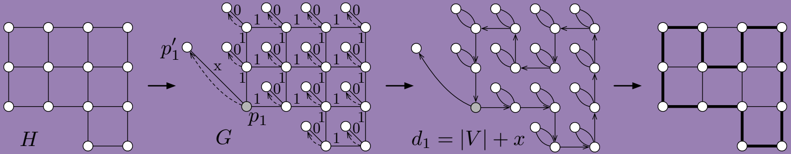
Which route should each agent take?

NP-hard on planar graphs even for a single agent:



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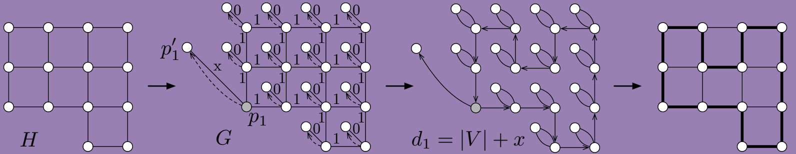

Similarly: NP-hard to approximate better than $1 + \frac{1}{122} \cdot \frac{1}{3} = \frac{367}{366}$.

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Planning
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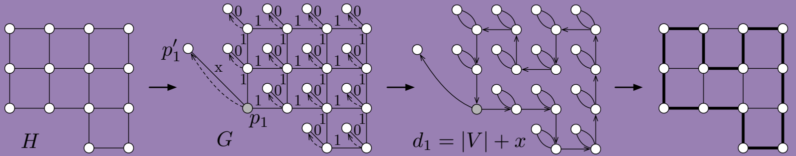


Similarly: NP-hard to approximate better than $1 + \frac{1}{122} \cdot \frac{1}{3} = \frac{367}{366}$.

Theorem (Planning restricted to direct delivery)

For $\kappa = 1$, restricted planning can be 2−approximated.

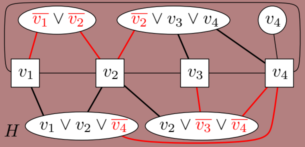
Proof Idea:

1. Build a minimum spanning tree that contains all (s_i, t_i)-edges, adding the other edges in a Kruskal-like fashion.
2. Traverse the minimum spanning tree twice.

Collaboration
Planning
Coordination

How should the agents be assigned to the messages?

NP-hard on planar graphs even in simple cases, where there is no collaboration and a total message order:



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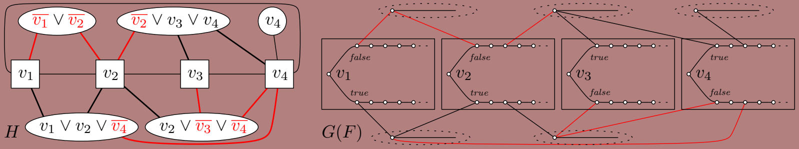

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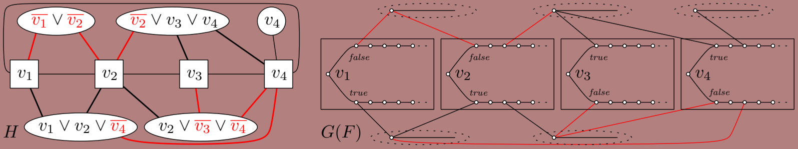

Theorem

For $\kappa = 1$ and uniform weights, and given complete information about collaboration and planning, coordination can be solved in polynomial time.

Increasing each weight to uniform weight $w_{\max}$ thus gives a $\frac{w_{\max}}{w_{\min}}$-approximation of coordination.

Conclusion

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Collaboration

Planning

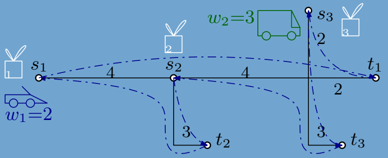
Coordination

$\underline{\kappa = 1}$: Increasing all weights to uniform weight $w_{\max}$ results in a loss of at most a factor of $\frac{w_{\max}}{w_{\min}}$.

$\frac{w_{\max}}{w_{\min}}$

Conclusion (for capacity $\kappa = 1$)

Collaboration



$\underline{\kappa = 1}$: no collaboration

+ direct delivery + return:

$$\text{BoC} \leq 2.$$

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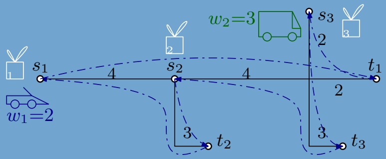

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Assign agents to messages (use no collaboration + direct delivery) paying attention only to their starting position.

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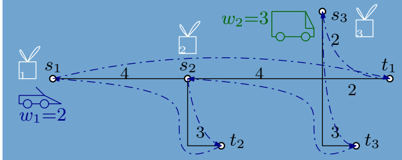

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$\underline{\kappa = 1}$: For each agent, compute traversal of a minimum spanning tree that connects its starting position to its subset of messages; direct delivery of each message $\rightarrow$ 2−approximation.

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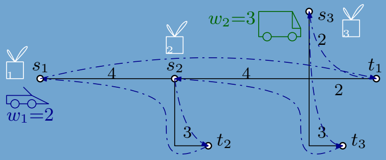
Open: $\kappa > 1$

Collaboration



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