Towards Uncertainty-Aware Path Planning On Road Networks Using Augmented-MDPs

Lorenzo Nardi and Cyrill Stachniss

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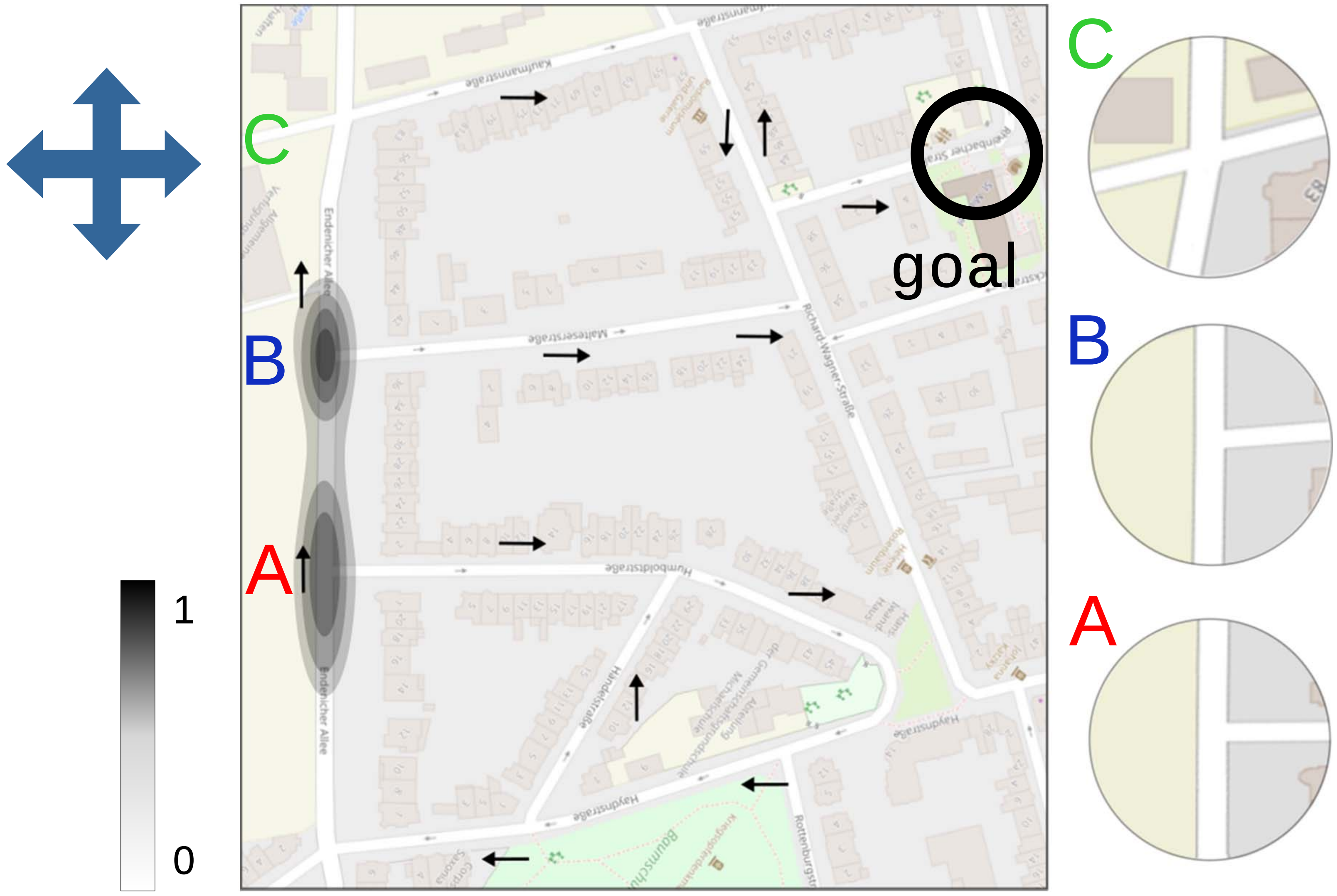
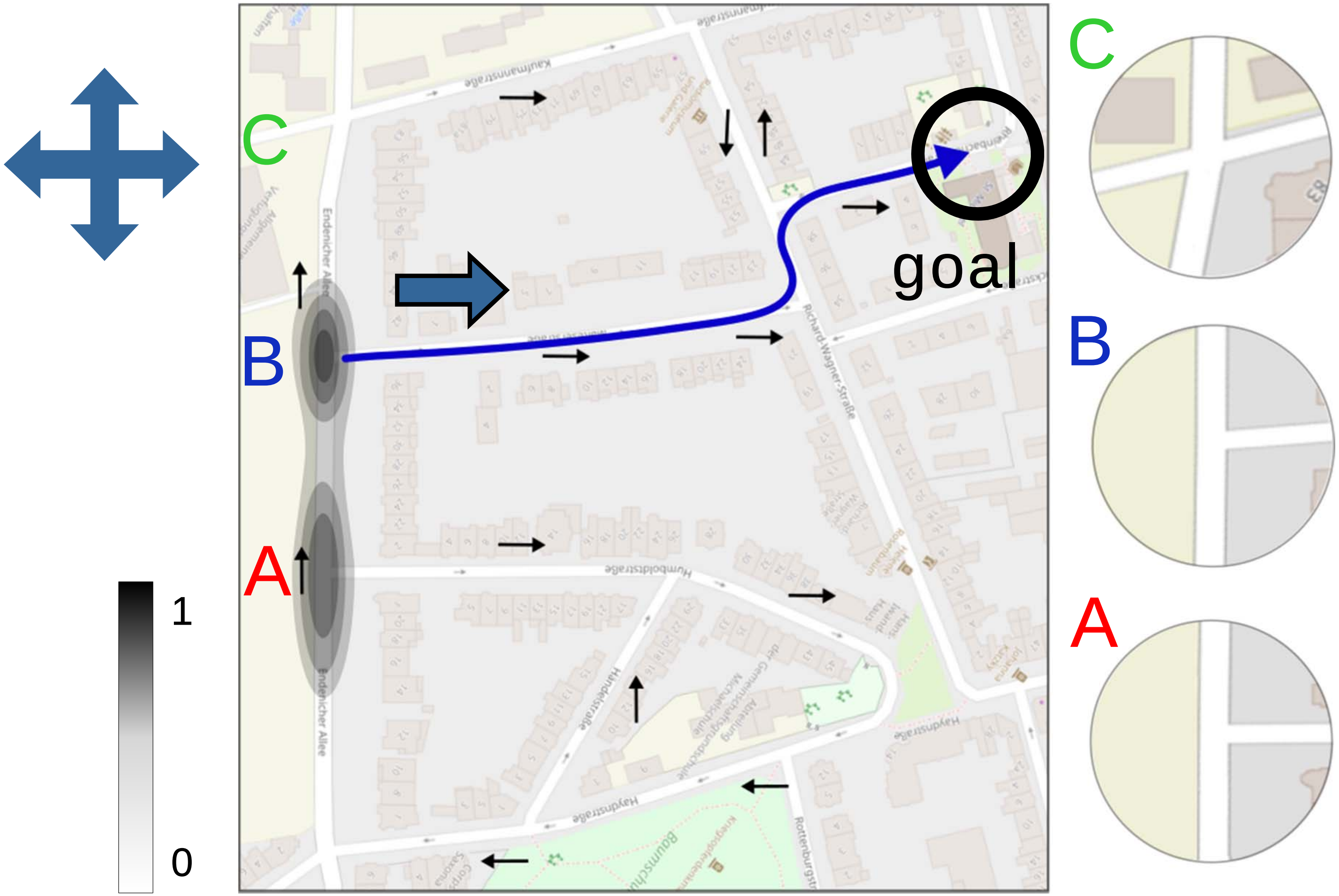
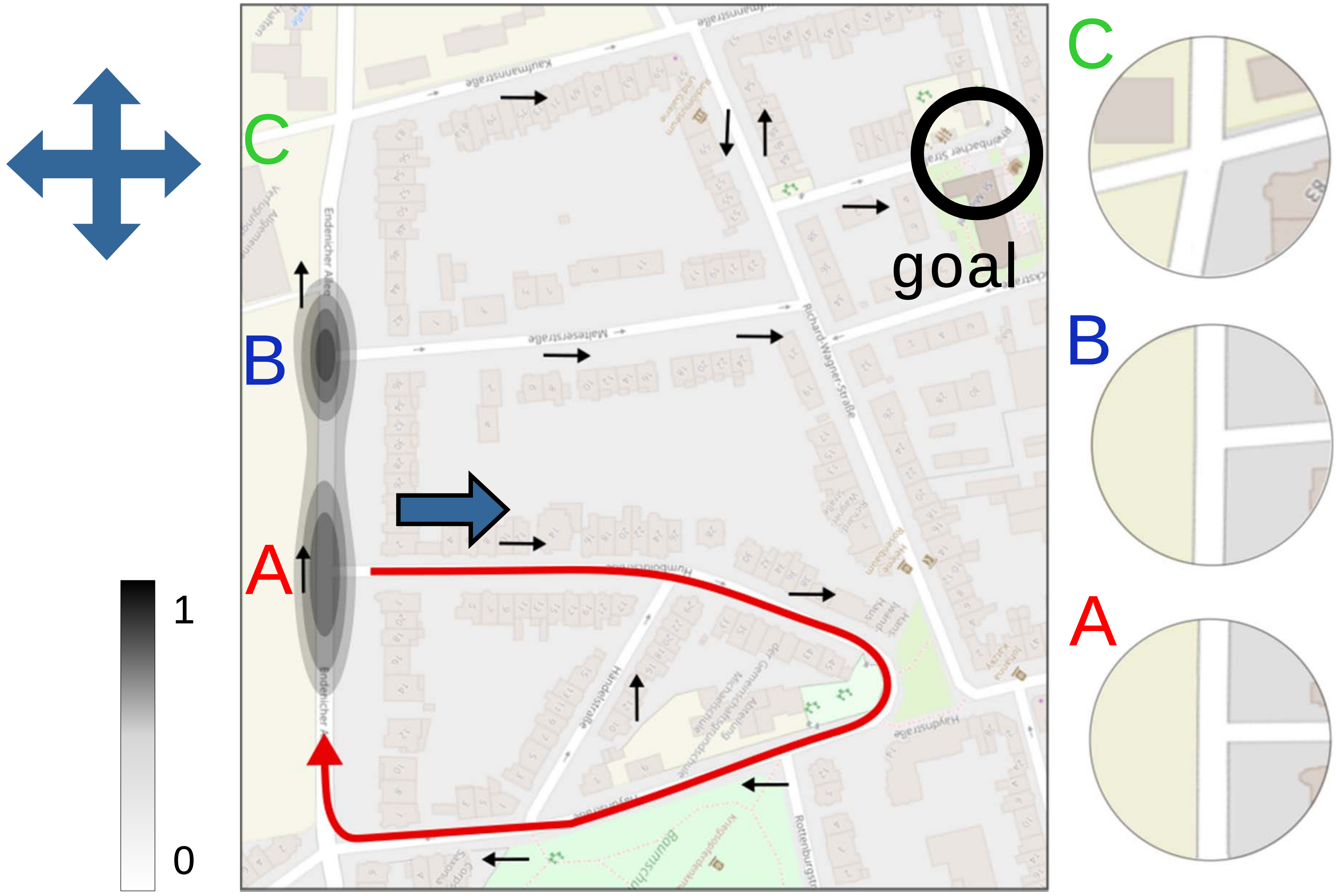
Navigation under uncertainty



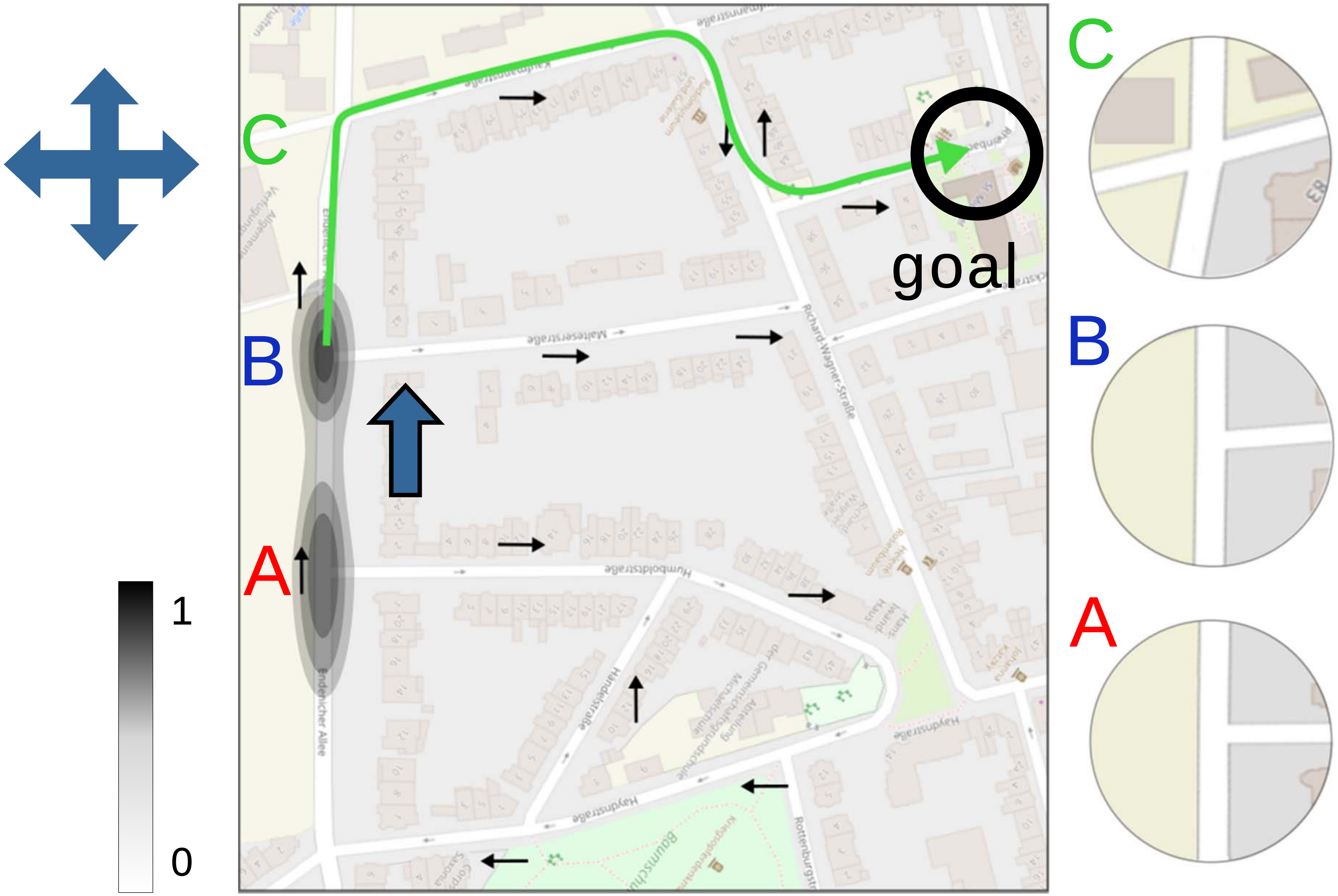
`B` is the most likely position



If the robot is at `A` instead



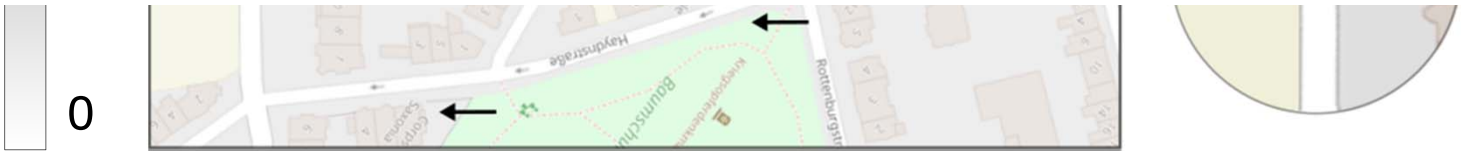
Safer to go up and turn at `C`



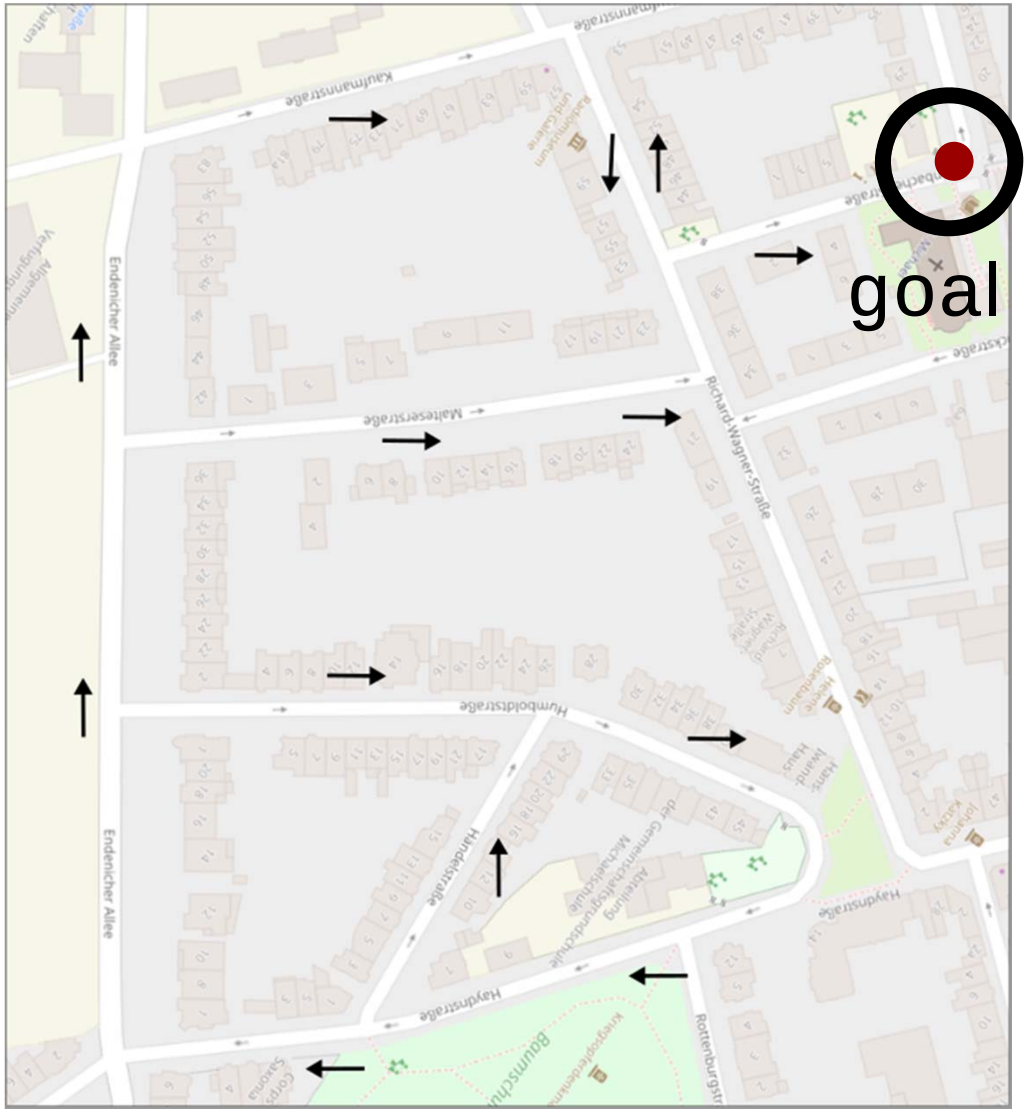
Safer to go up and turn at `C`

Objective

Select actions that **reduce the risk to make mistakes** during navigation with **large position uncertainty**



Planning on road networks



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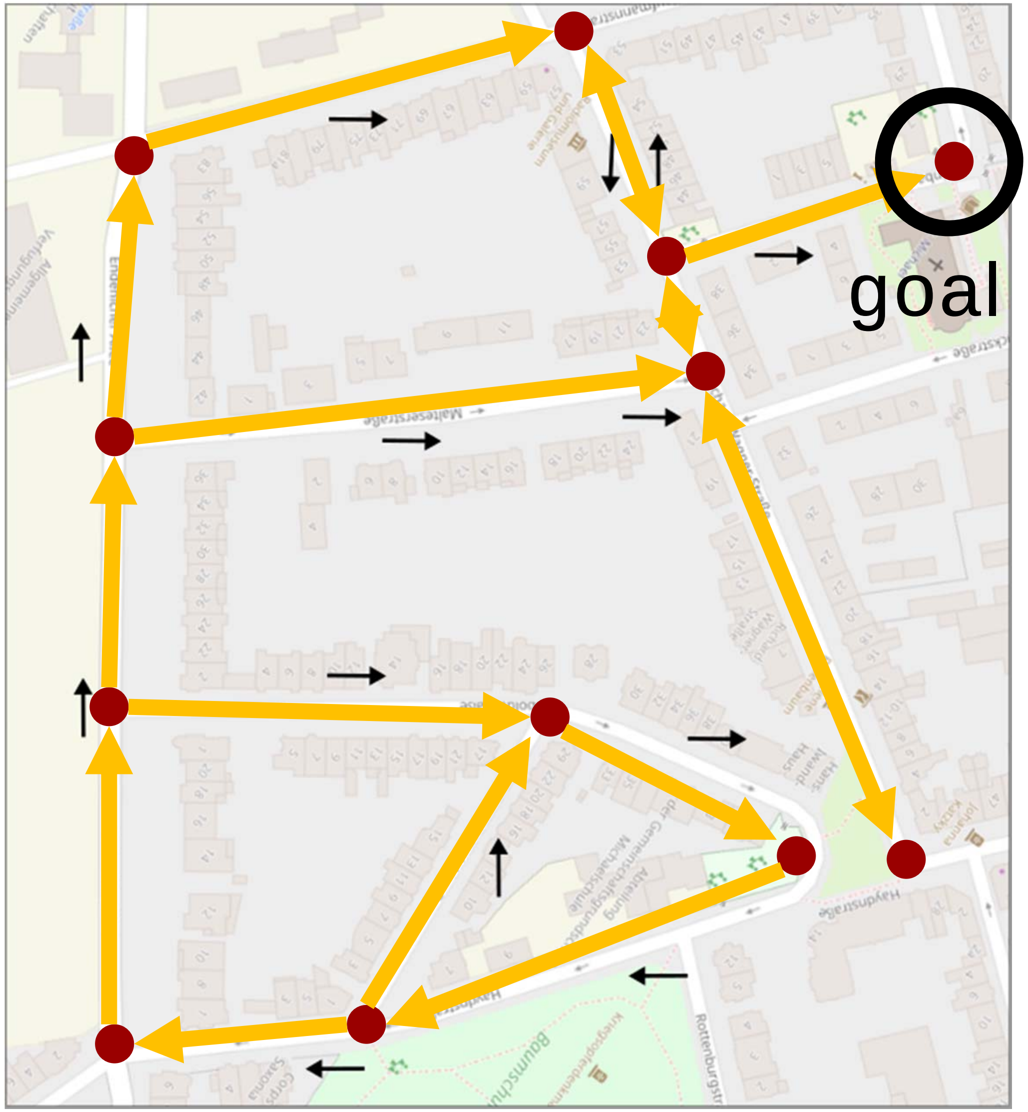
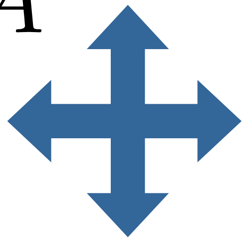
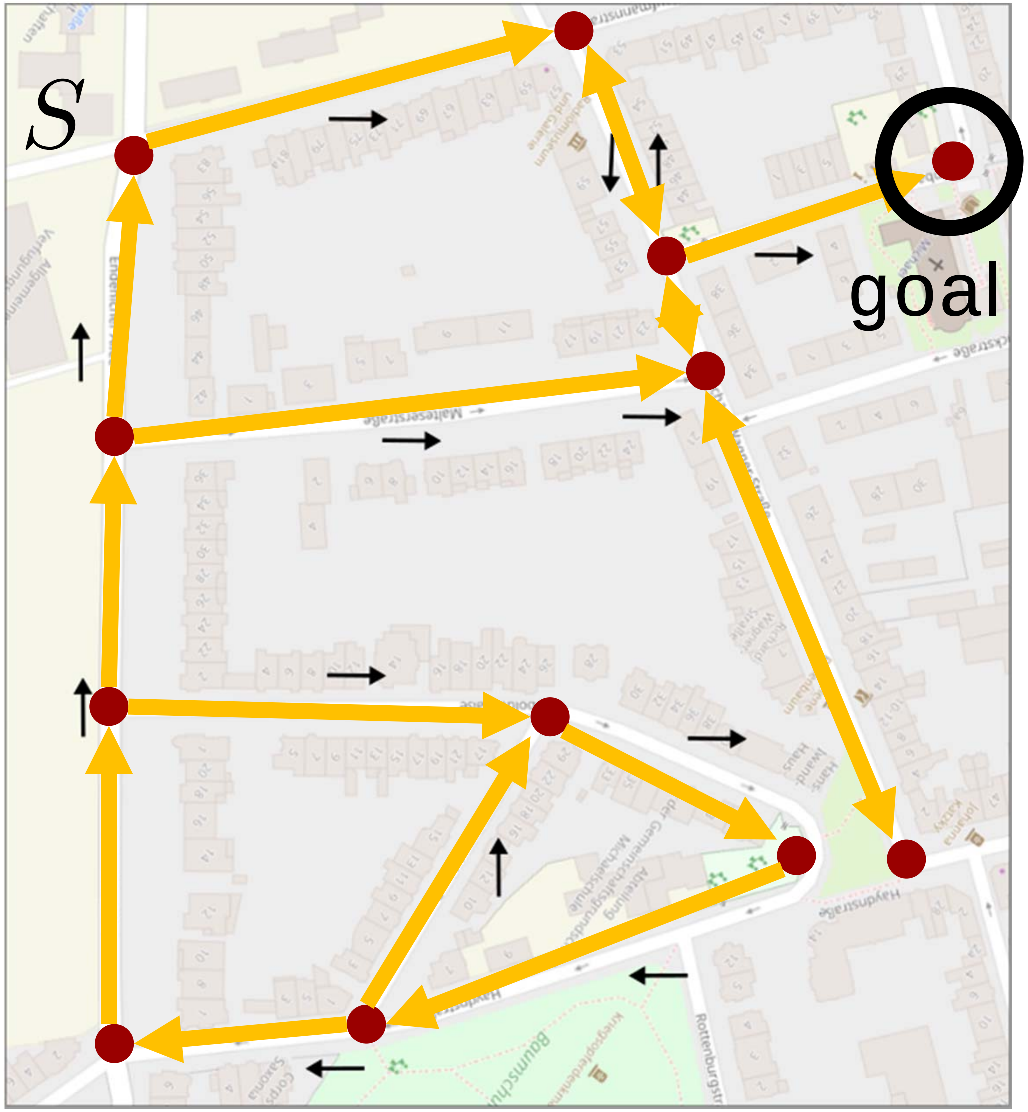


Markov Decision Process (MDP)

A



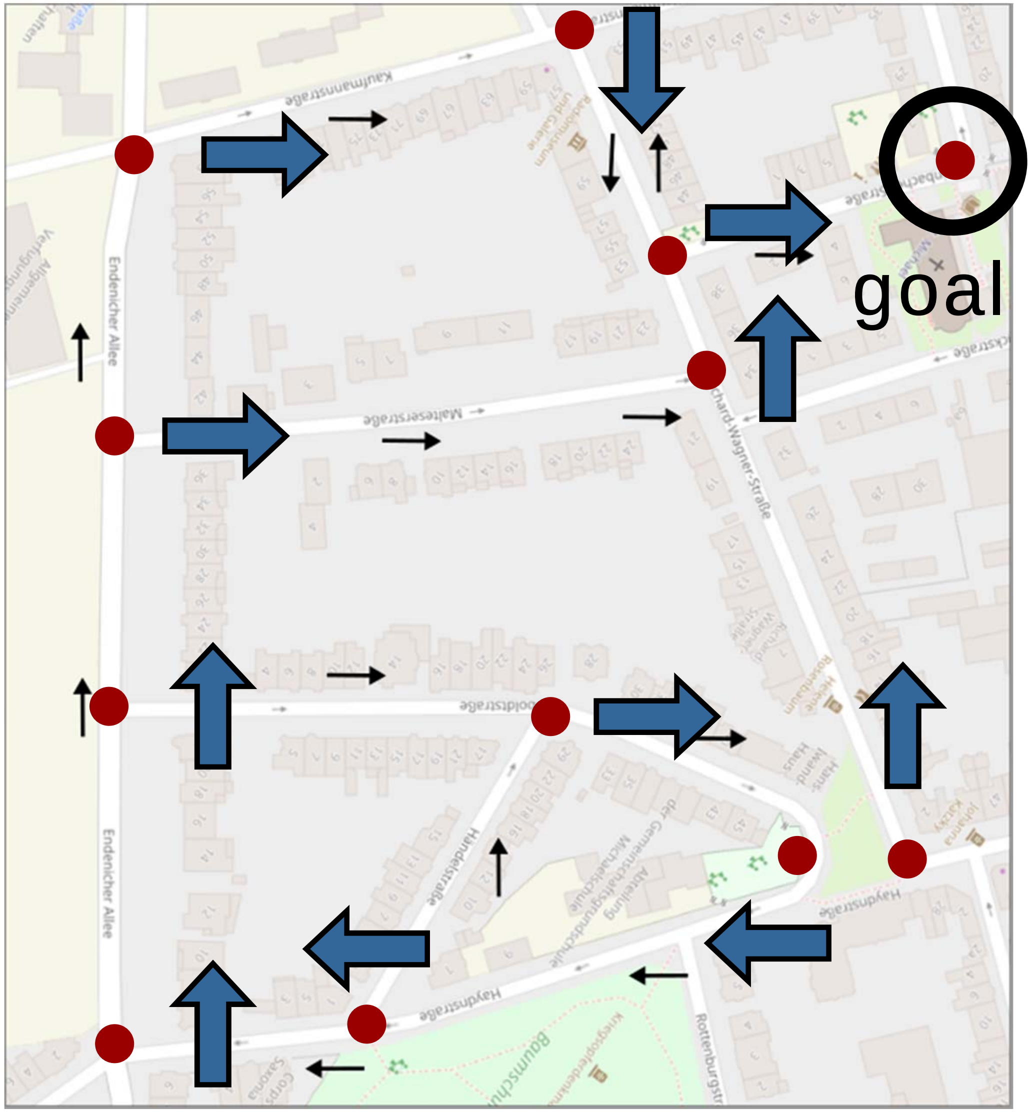
S



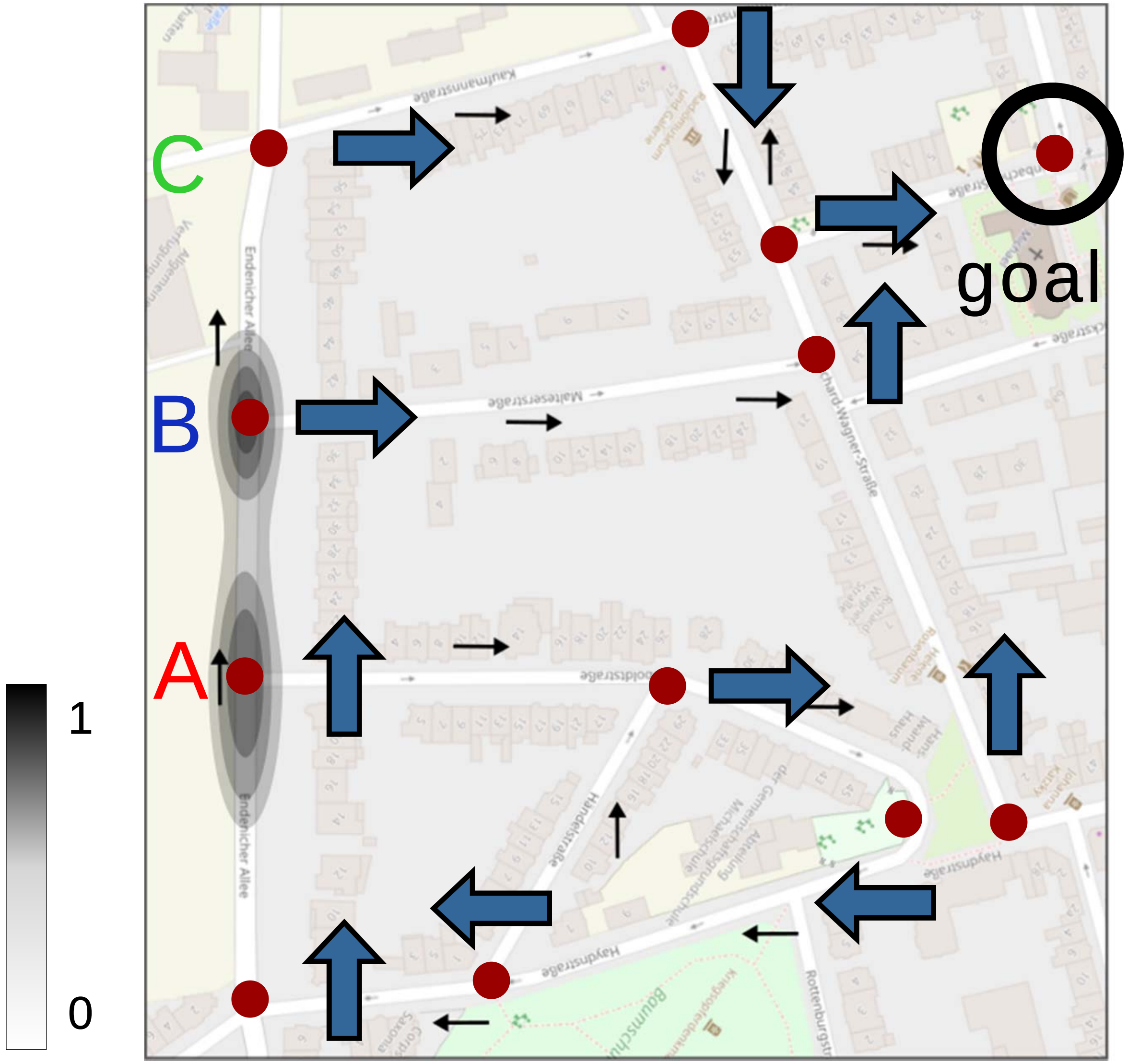
$$T(s, a, s')$$

$$R(s, a, s')$$

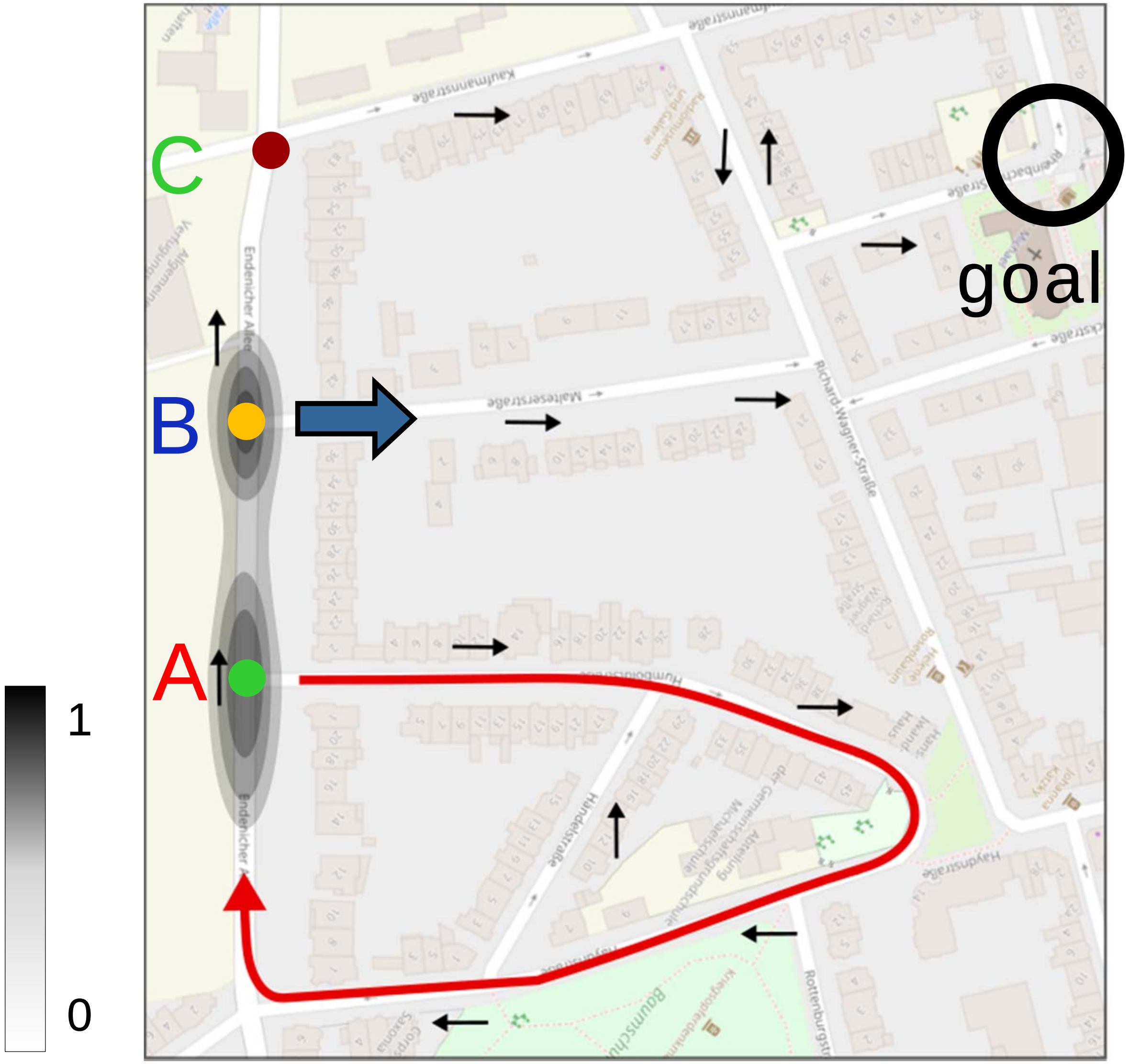
Optimal actions at intersections



MDP state is fully observable



Uncertainty is ignored



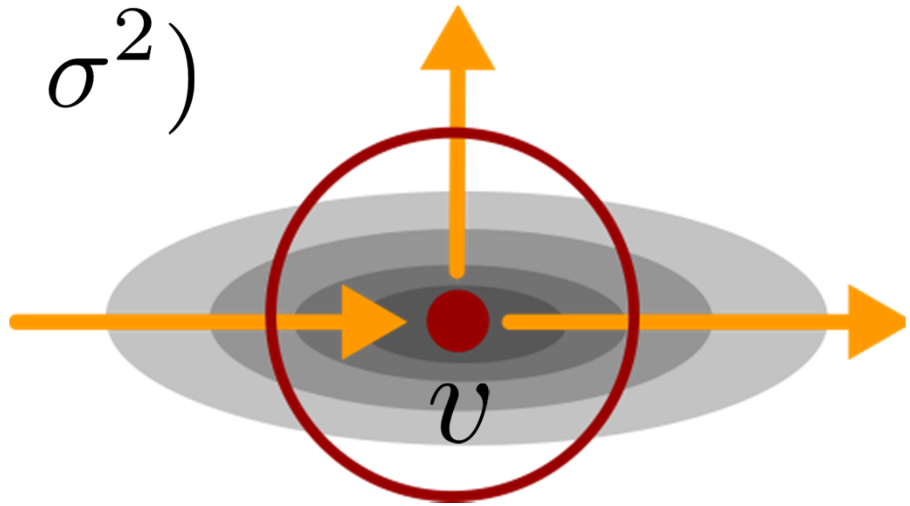
Uncertainty-aware planning

- **Reduce the risk** to make wrong navigation decisions
- Consider **position uncertainty** during planning
- General formulation as Partially Observable MDPs or **POMDPs**
- POMDPs are **hard to solve** for real-world applications

Augmented-MDPs (A-MDP)

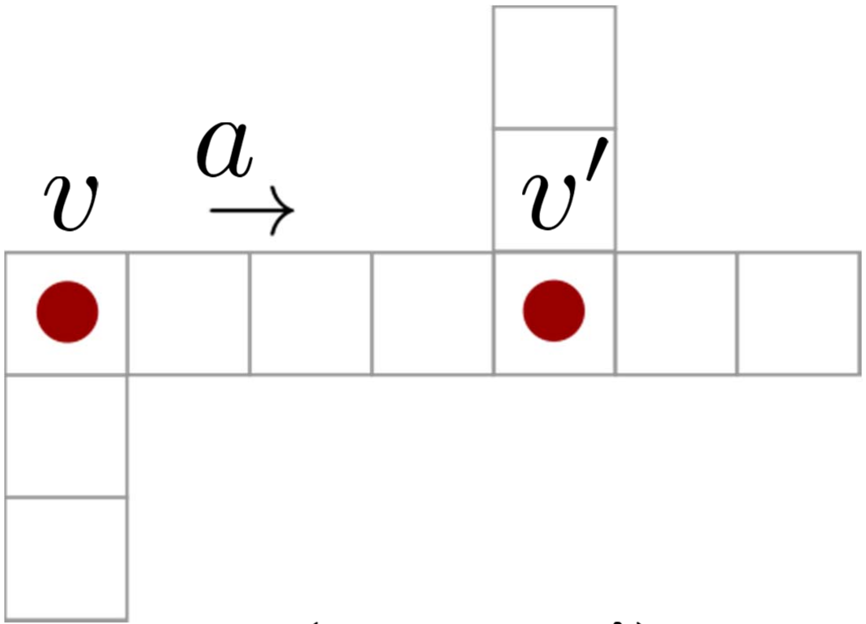
- **Efficient** POMDPs approximation
- **Augment MDP state** space with position uncertainty
- Approximate state estimate **during planning** with isotropic Gaussian

$$s = (v,\ \sigma^2)$$



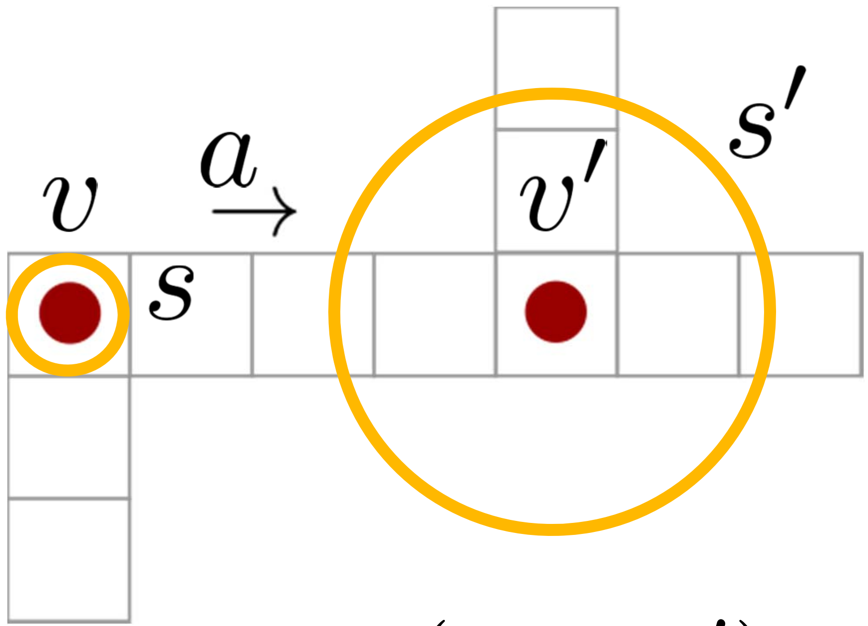
Transitions between beliefs

MDP



$$T(v, a, v')$$

A-MDP

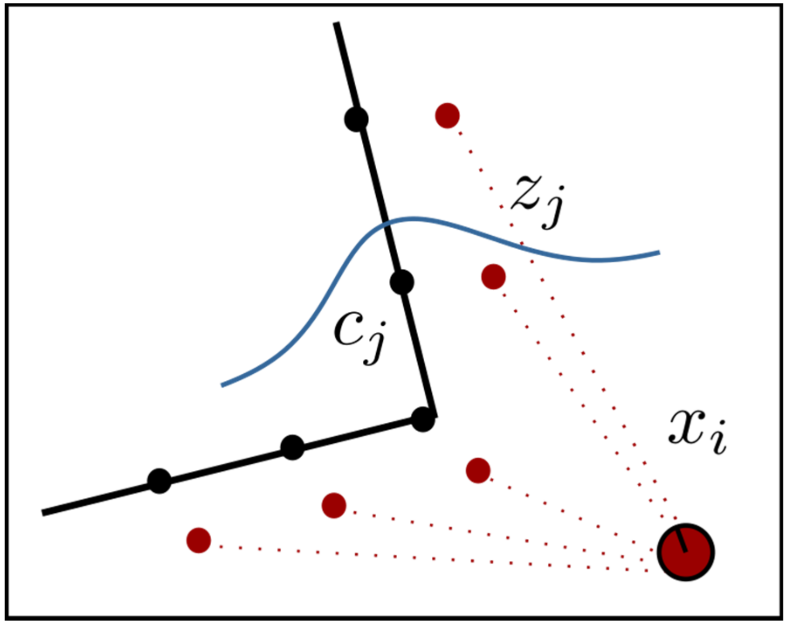


$$T(s, a, s')$$

Localizability information

Estimate the **localization accuracy**

OpenStreetMap



Vysotska et al. 2017

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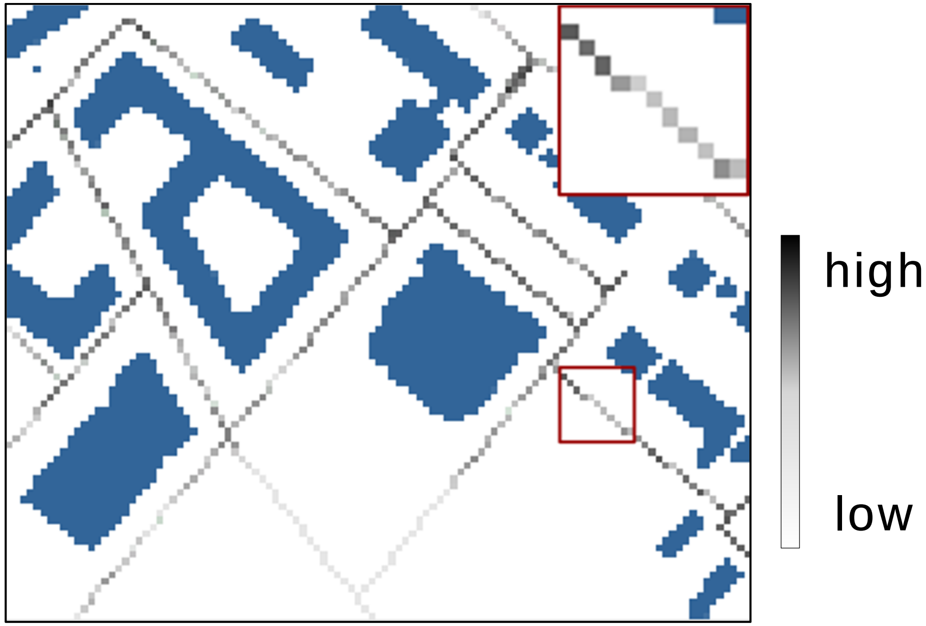
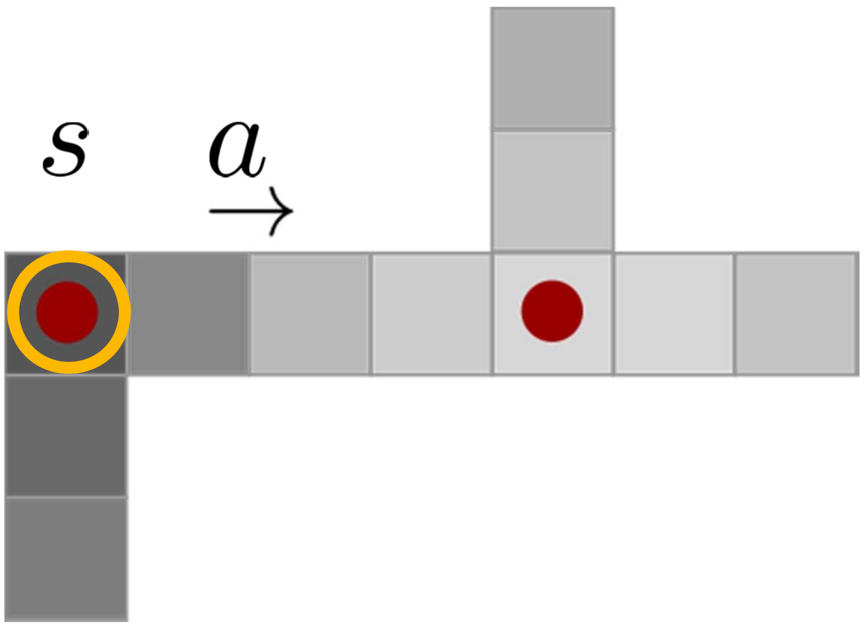


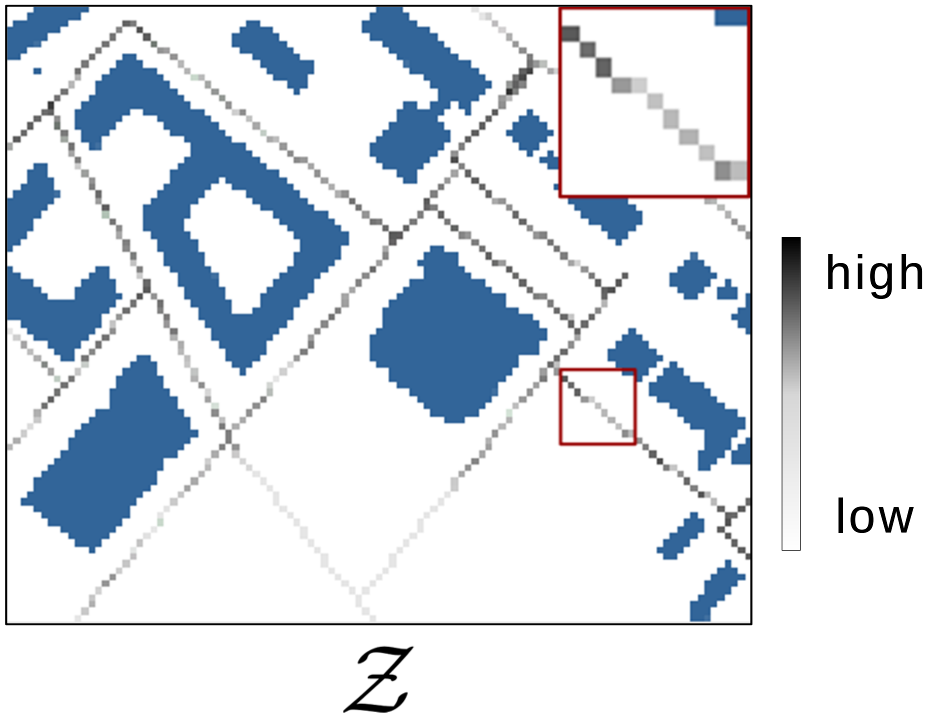
$\mathcal{Z}$

EKF prediction + Localizability

Estimate the **belief propagation**

$$p(x_t \mid x_{t-1}, u_t, \mathcal{Z}) = \mathcal{N}(\hat{\mu}_t, (\hat{\Sigma}_t^{-1} + \underline{\Sigma_{\hat{\mu}_t, \mathcal{Z}}^{-1}})^{-1})$$





EKF prediction + Localizability

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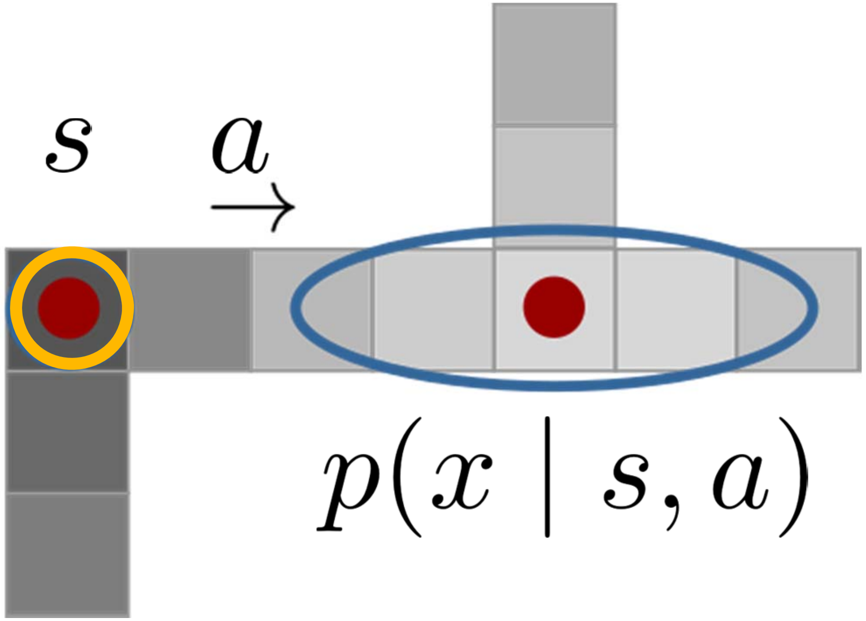
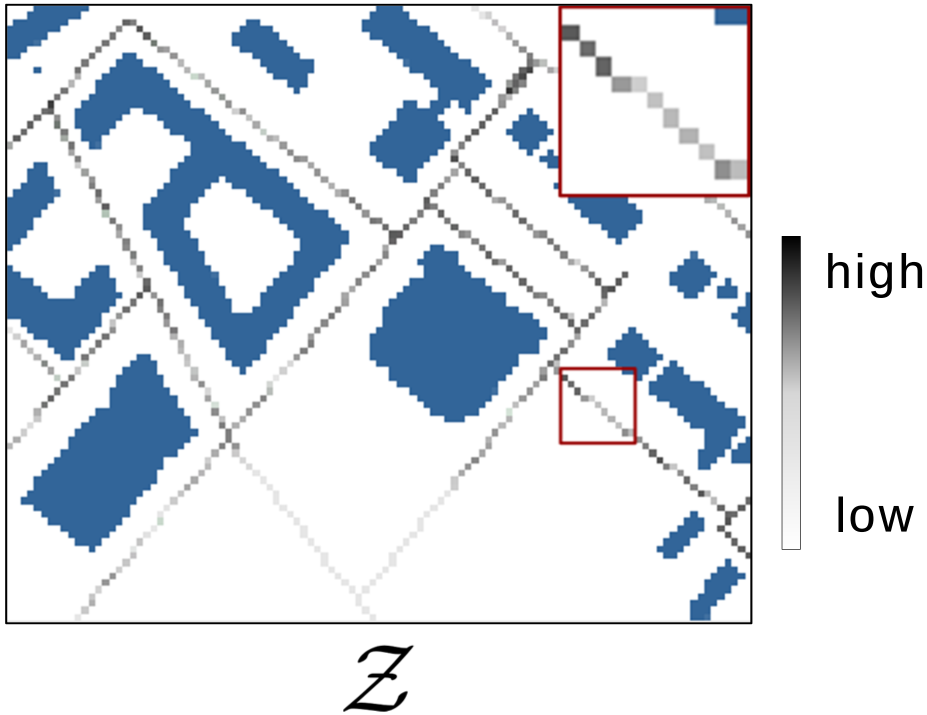
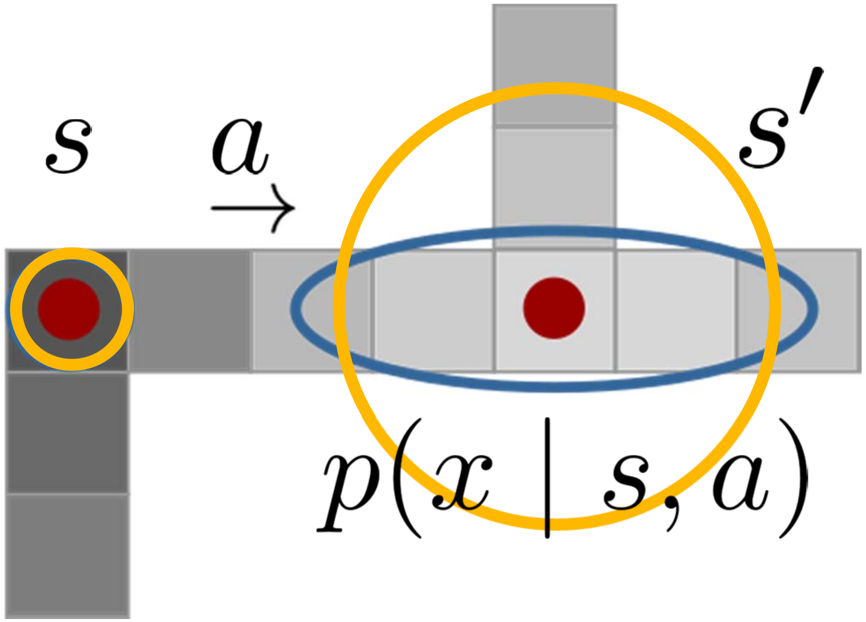


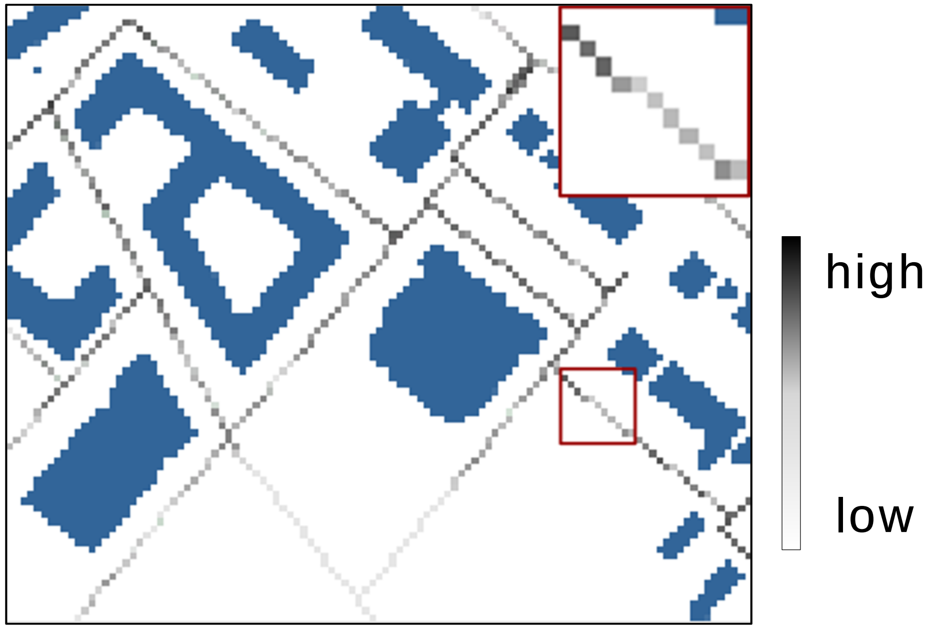


Transition probability

According to **Bhattacharyya distance** between **posterior** and **output state**



$$T(s, a, s')$$



Augmented-MDP

- Transitions **between beliefs**
- Rewards **minimize the travel time**

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- Representation **analogous to MDPs**
- But **larger number of states**
- Solve using Policy Iteration

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- Rewards minimize the travel time
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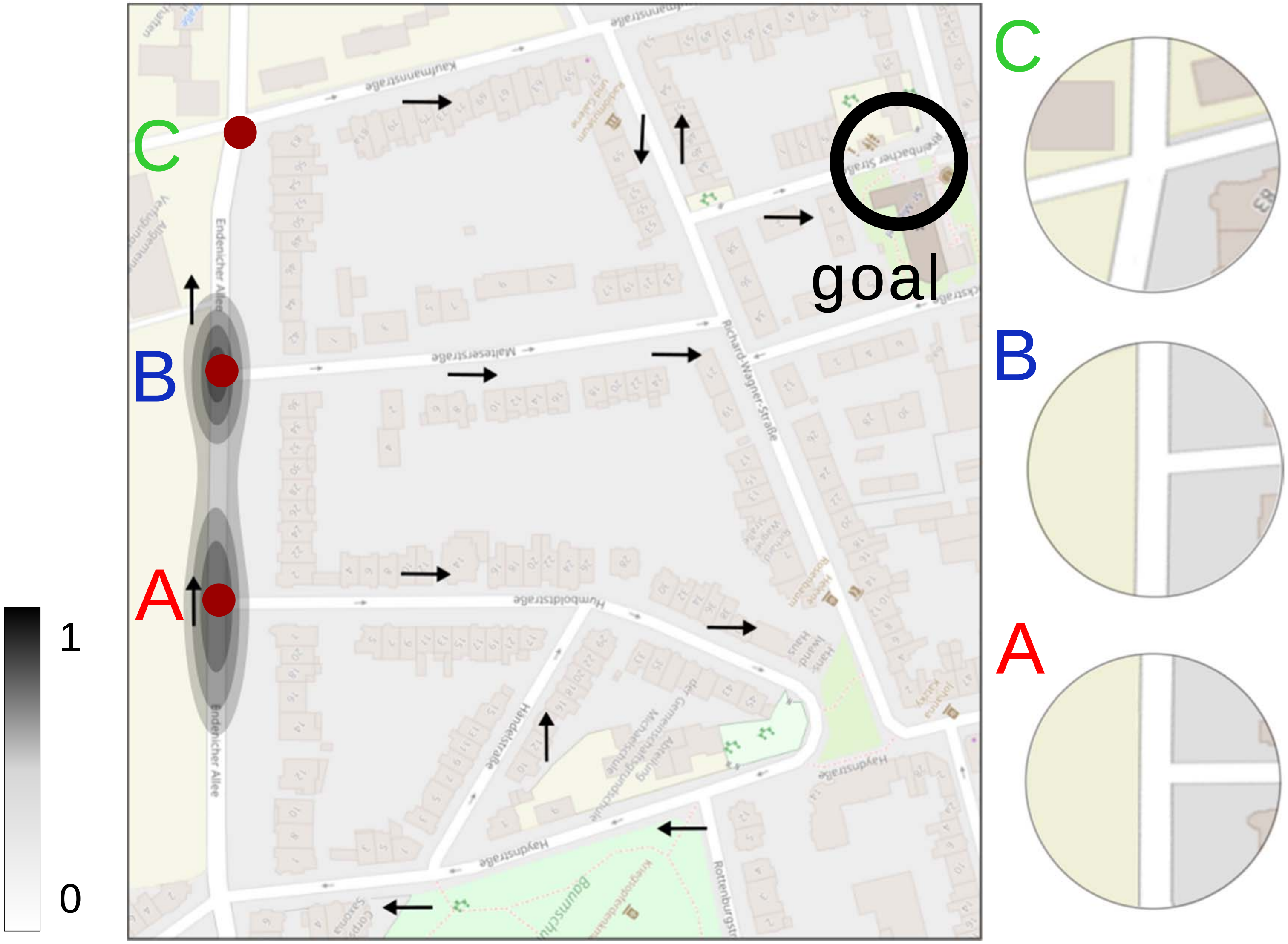
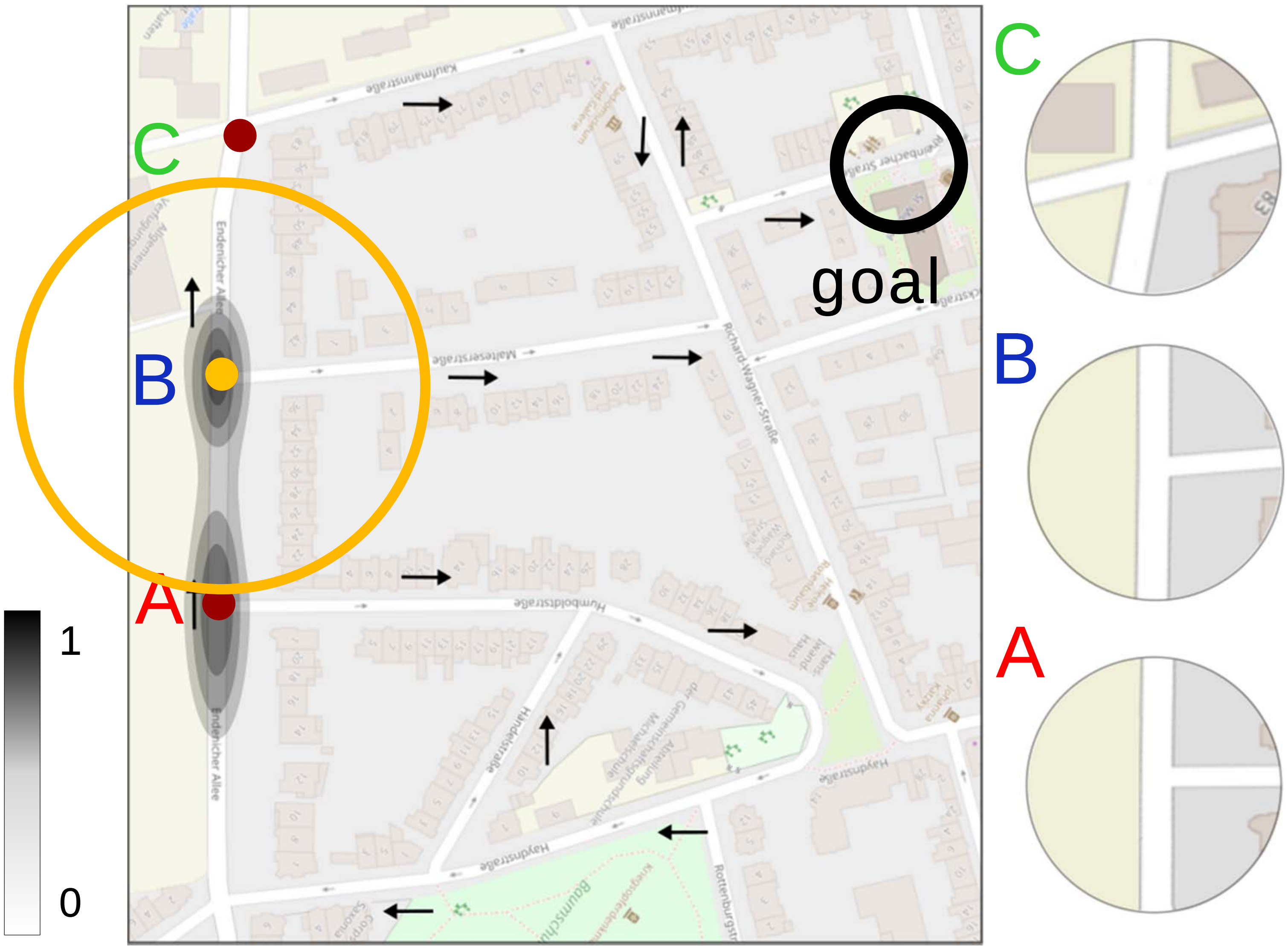
- But **larger number of states**
- Solve using Policy Iteration

Optimal policy **minimizes travel time** while **reducing the mistakes** during navigation

Uncertainty-aware decisions



Uncertainty-aware decisions



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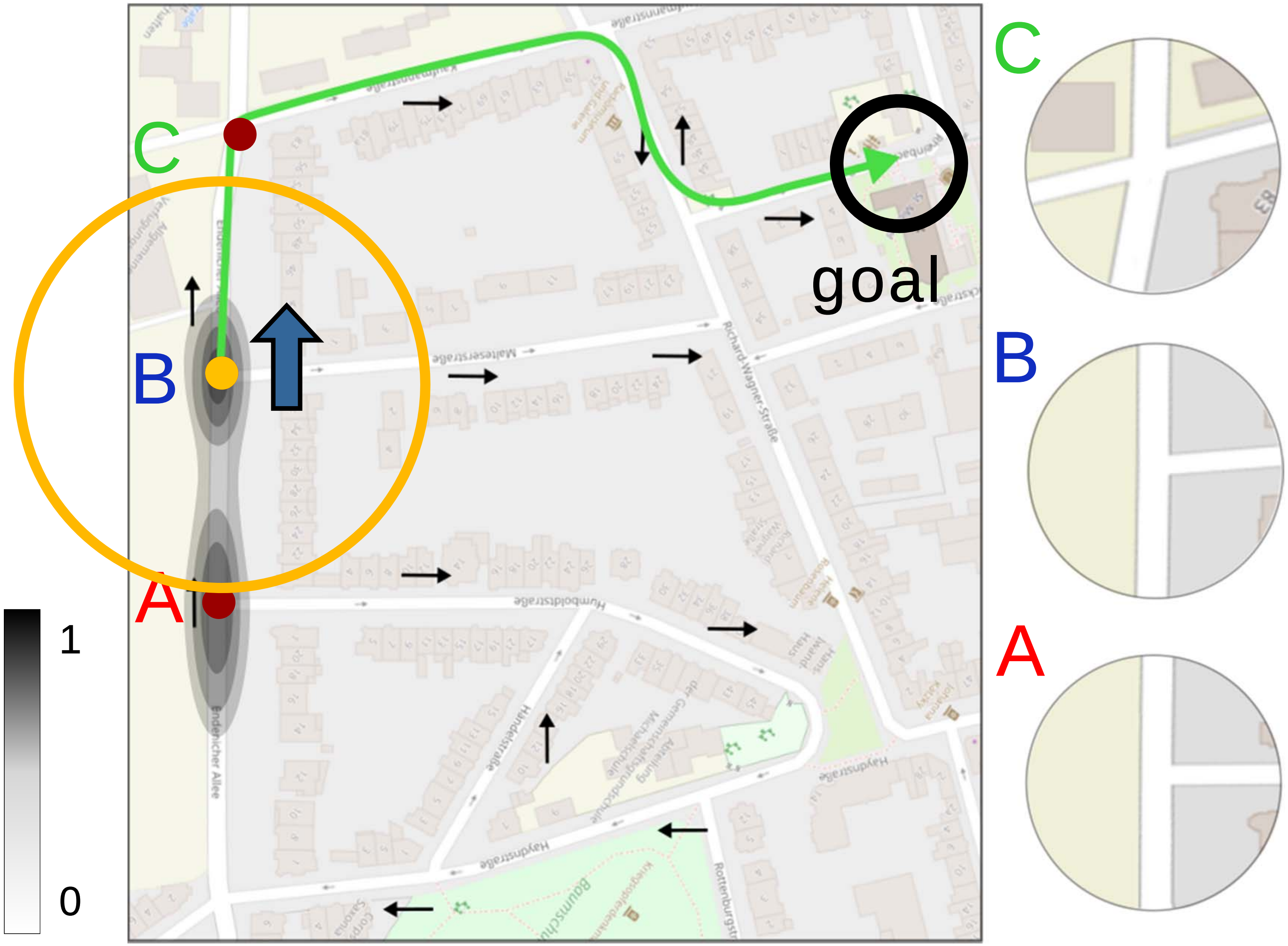

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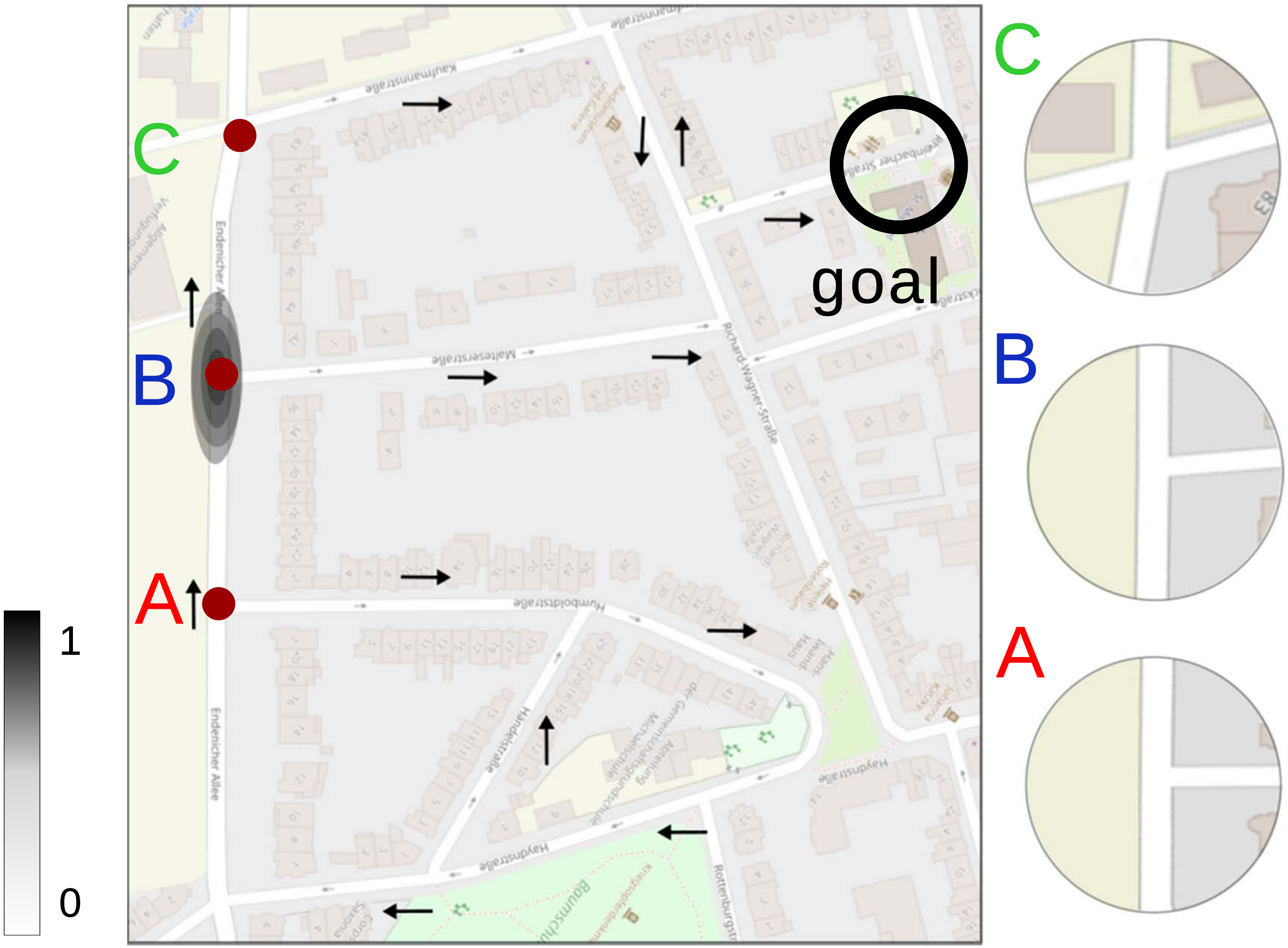

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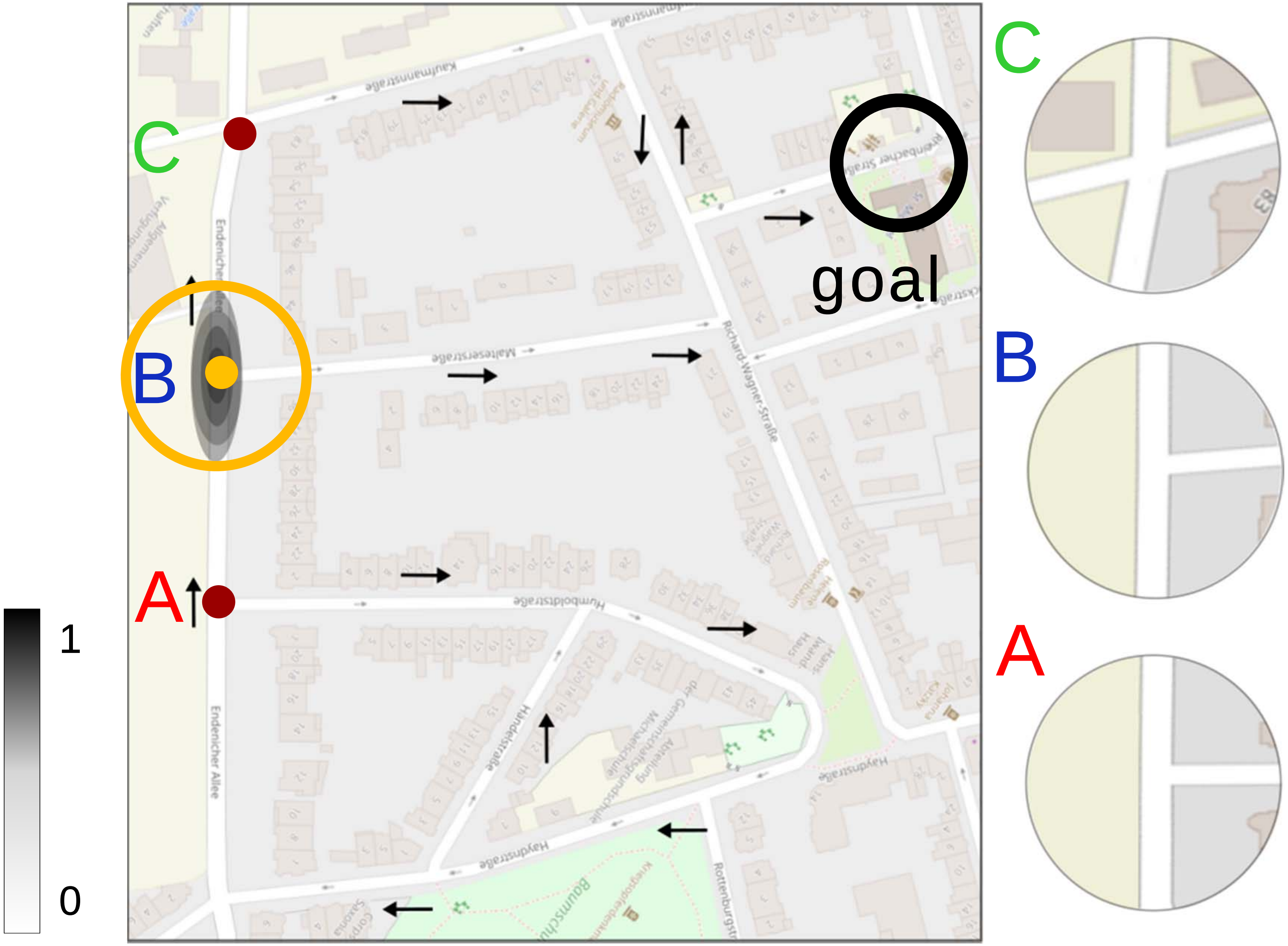
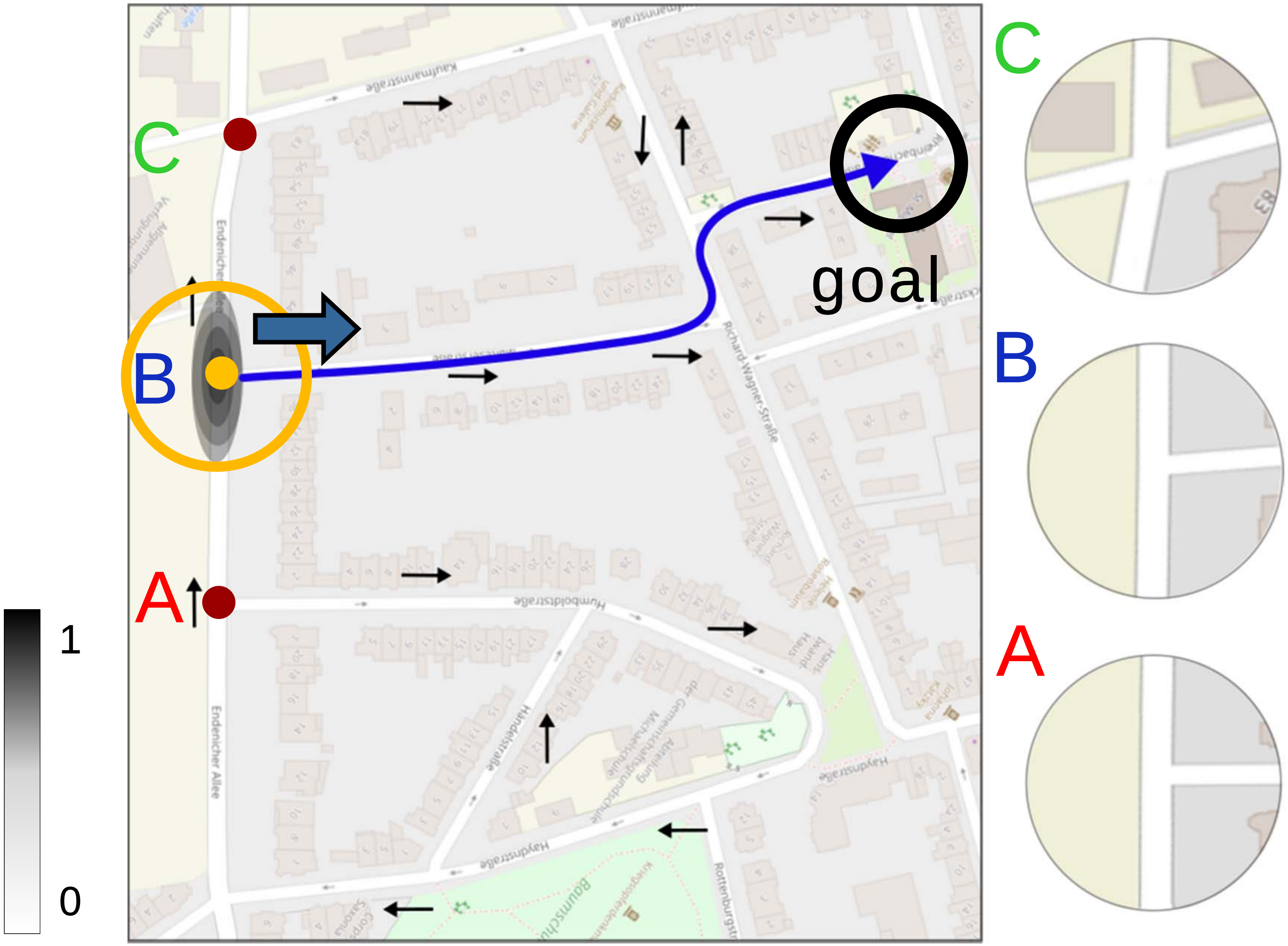
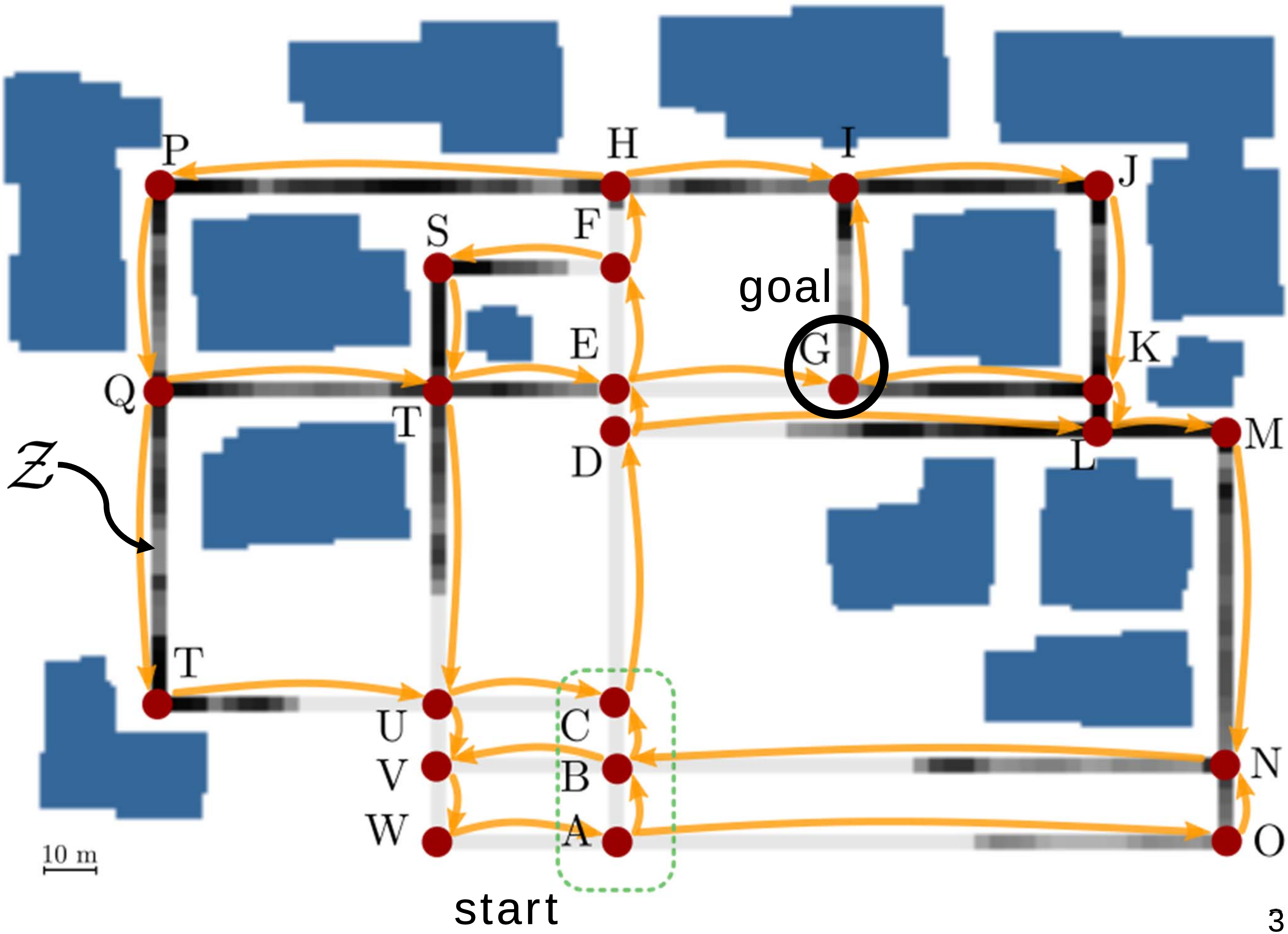


Uncertainty-aware decisions

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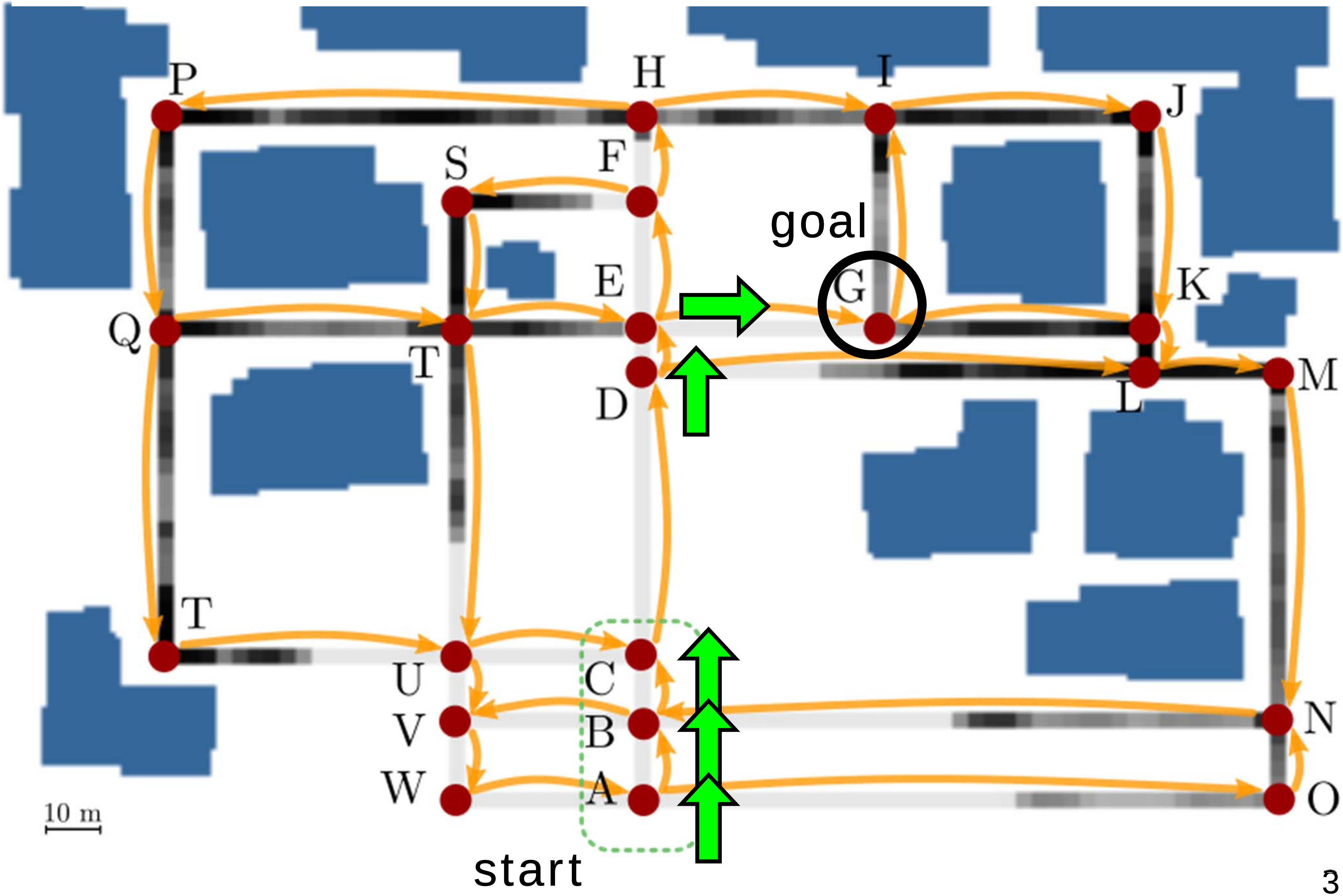
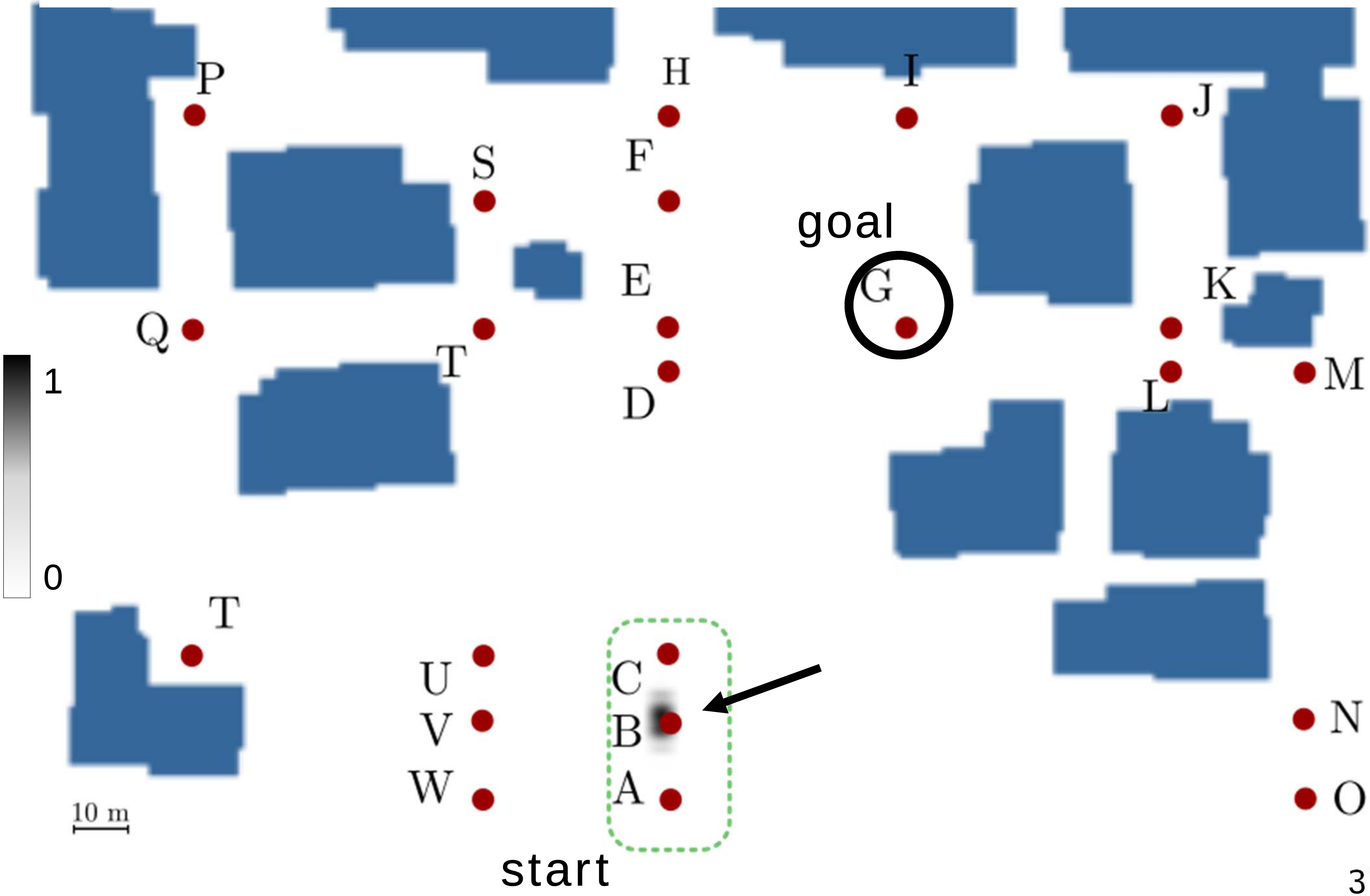
Shortest path policy



Shortest path, small uncertainty



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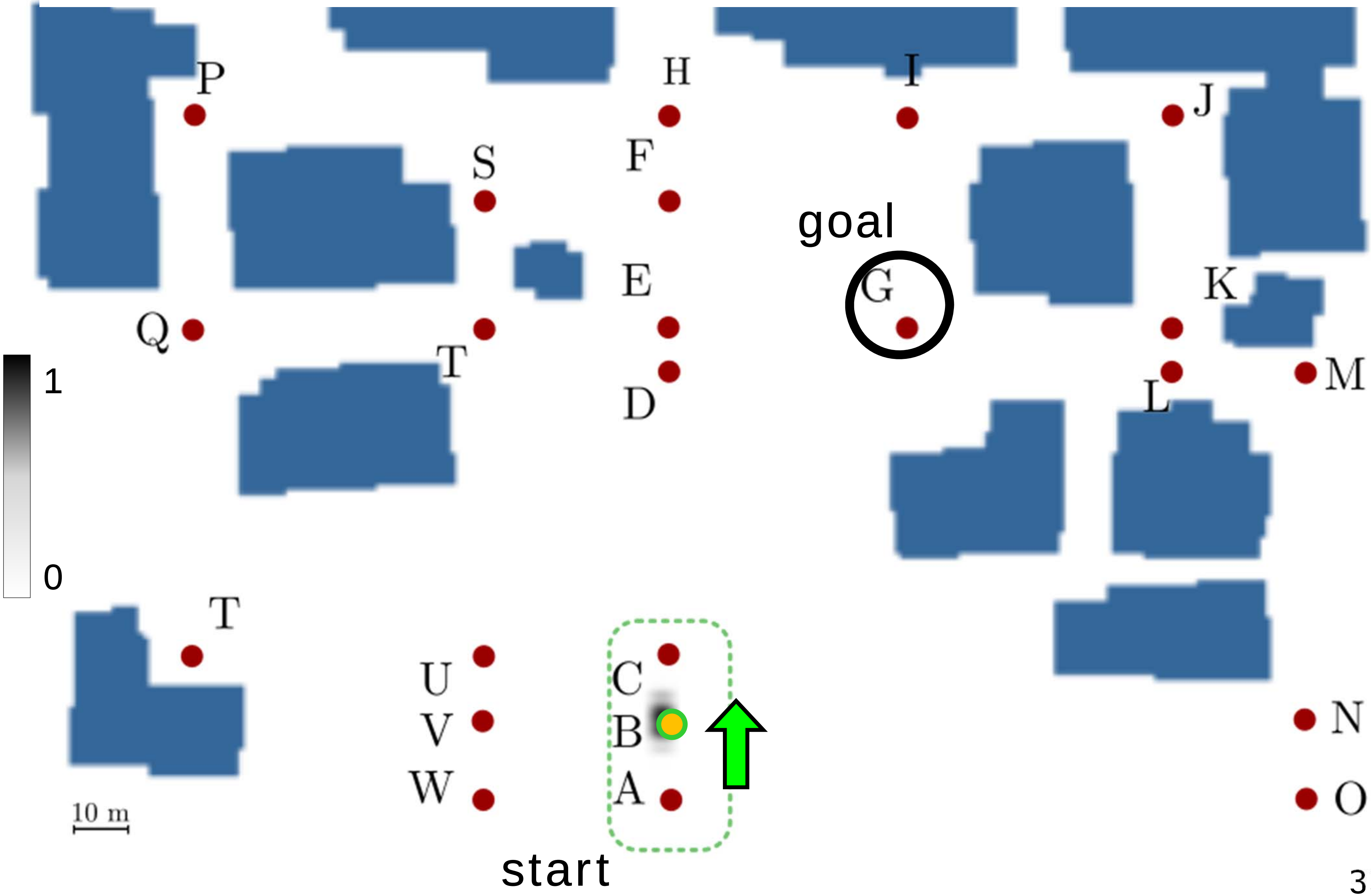

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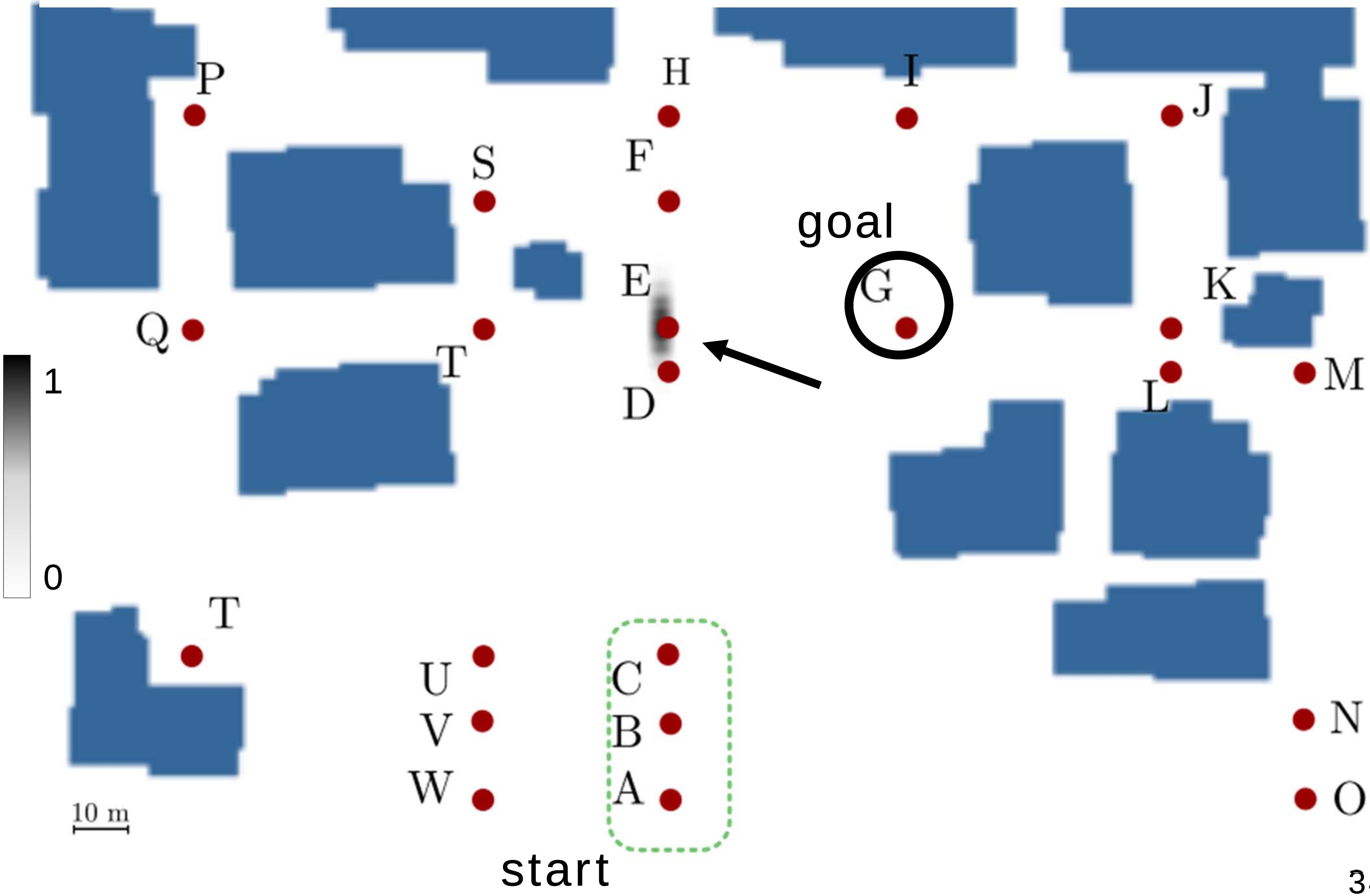

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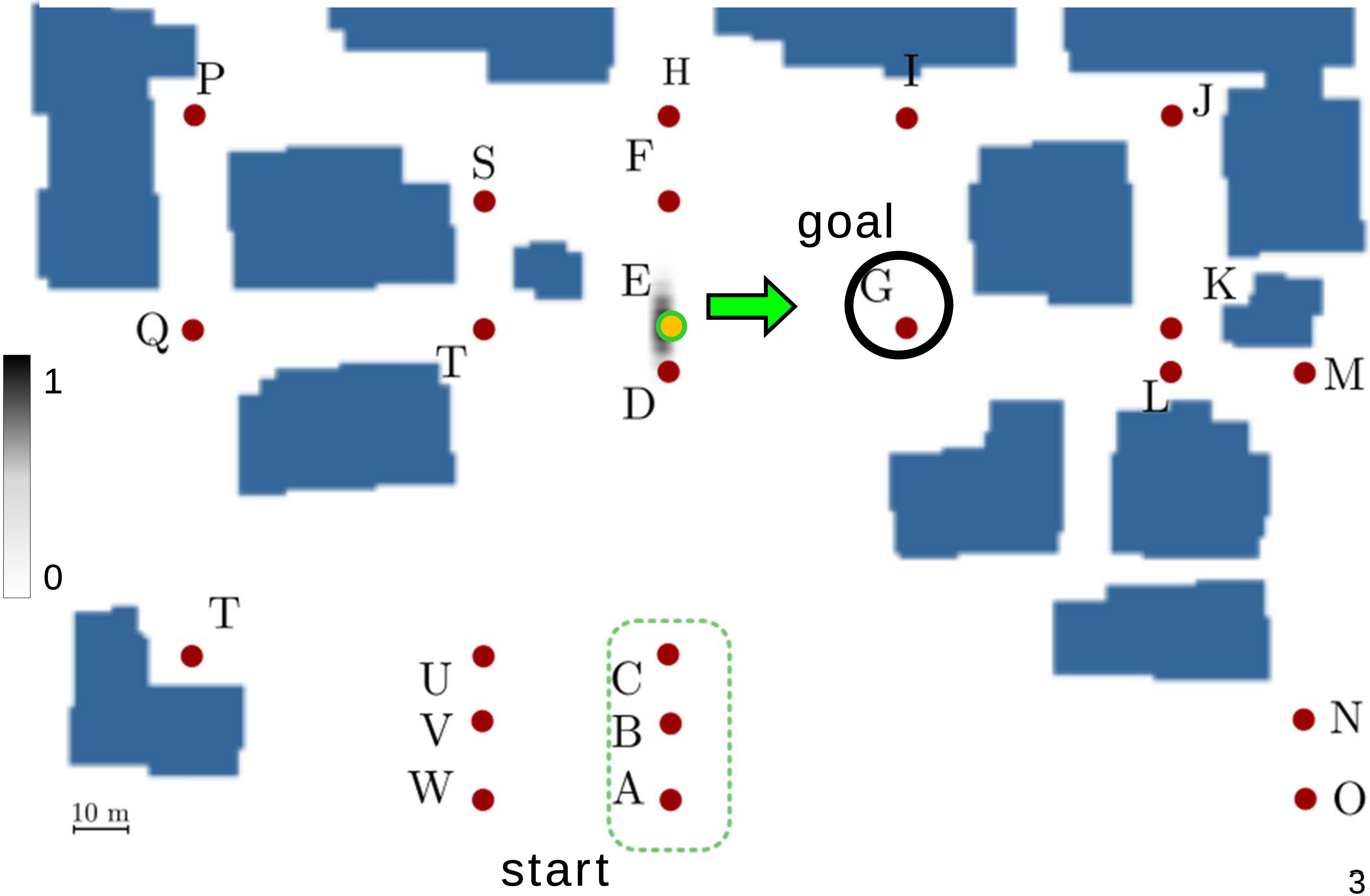

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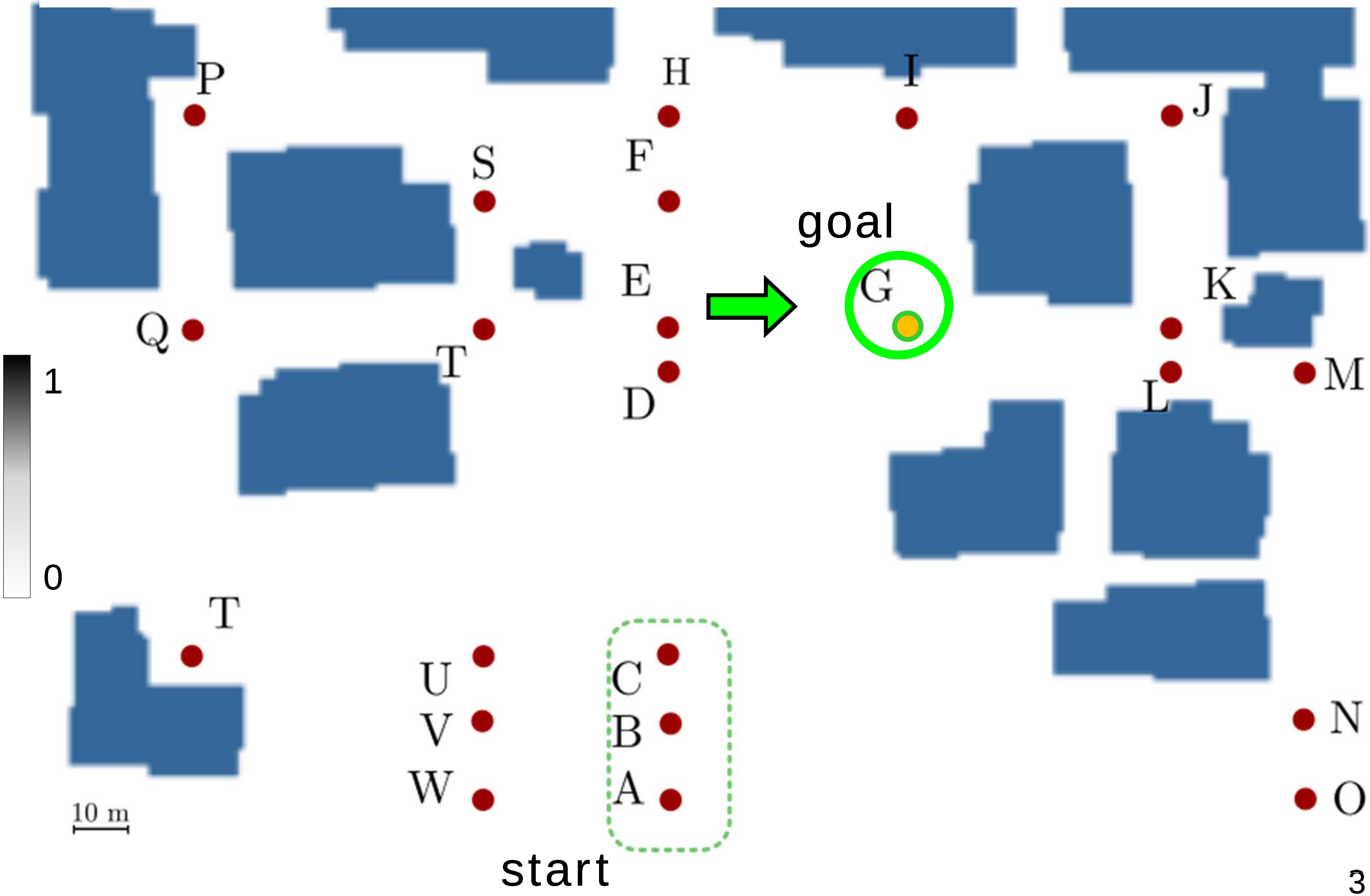

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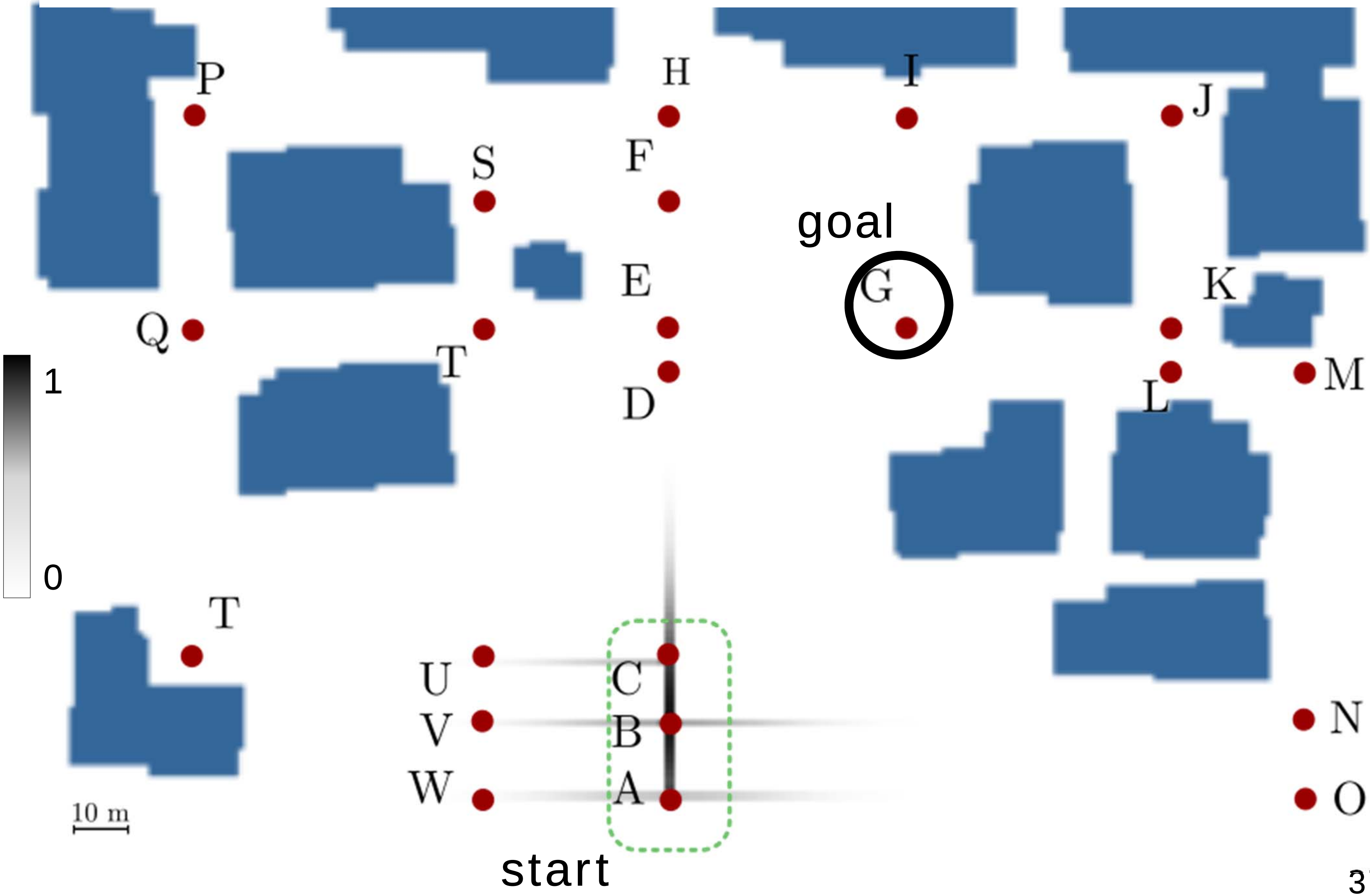

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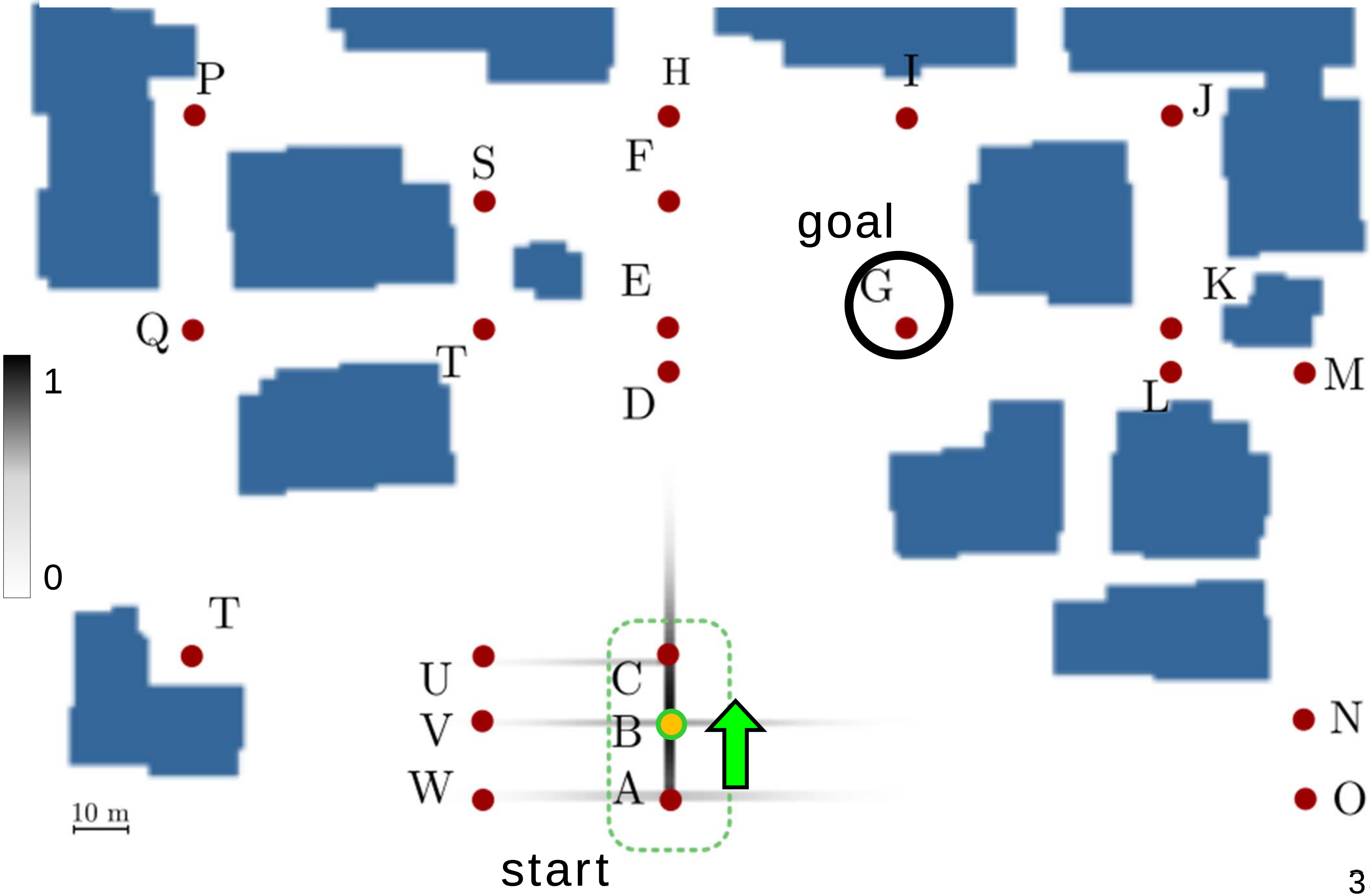

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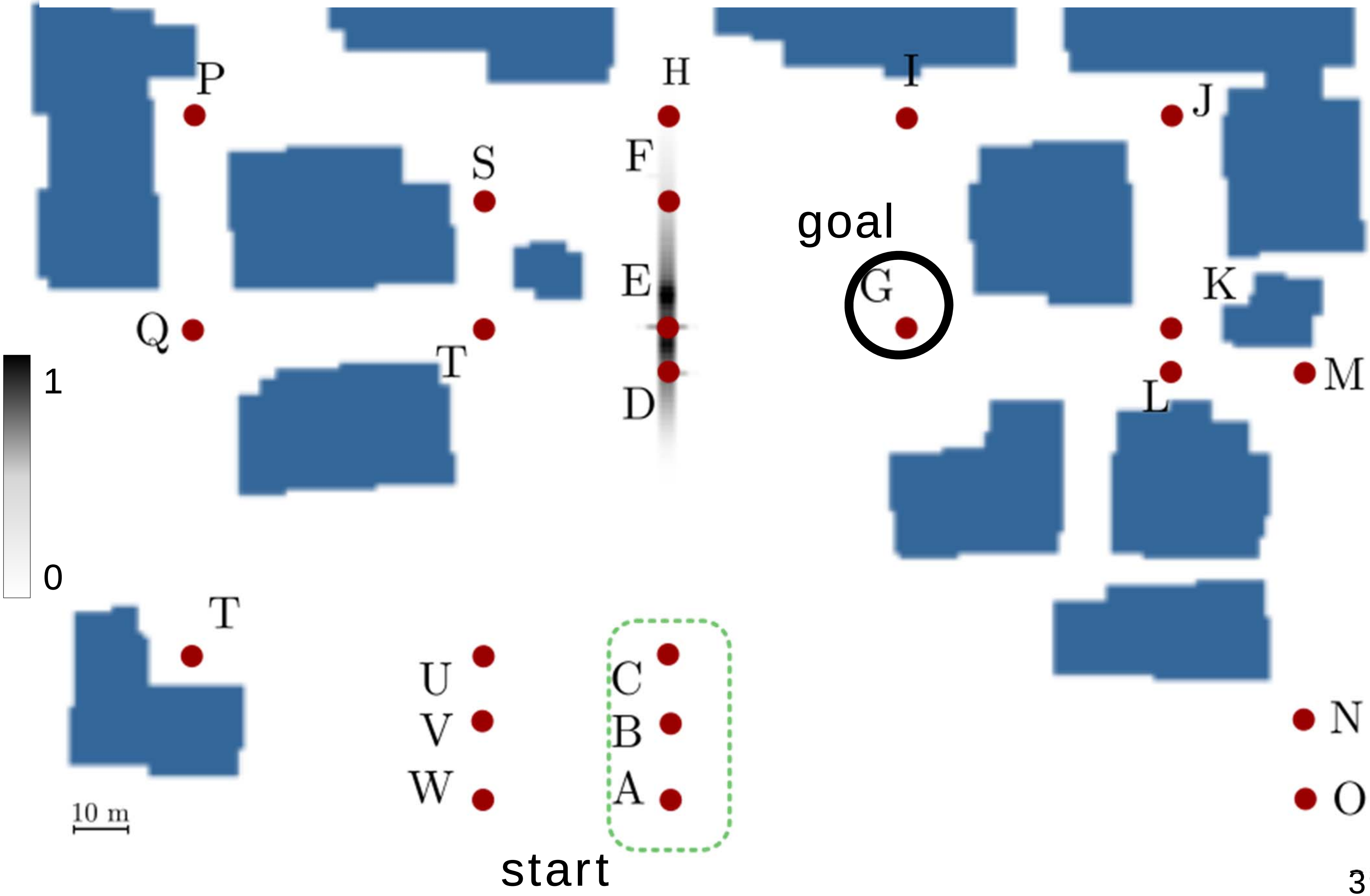

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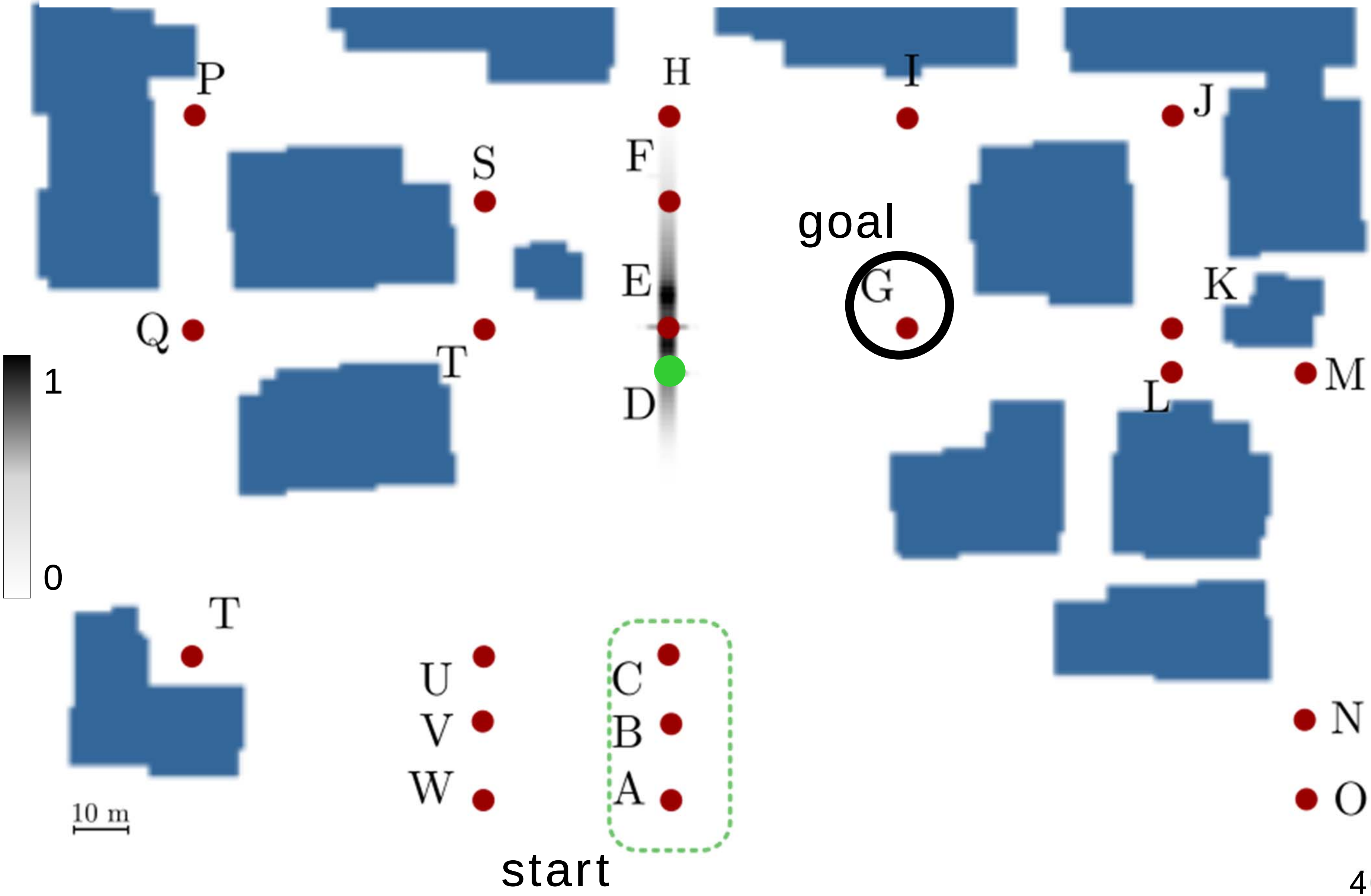

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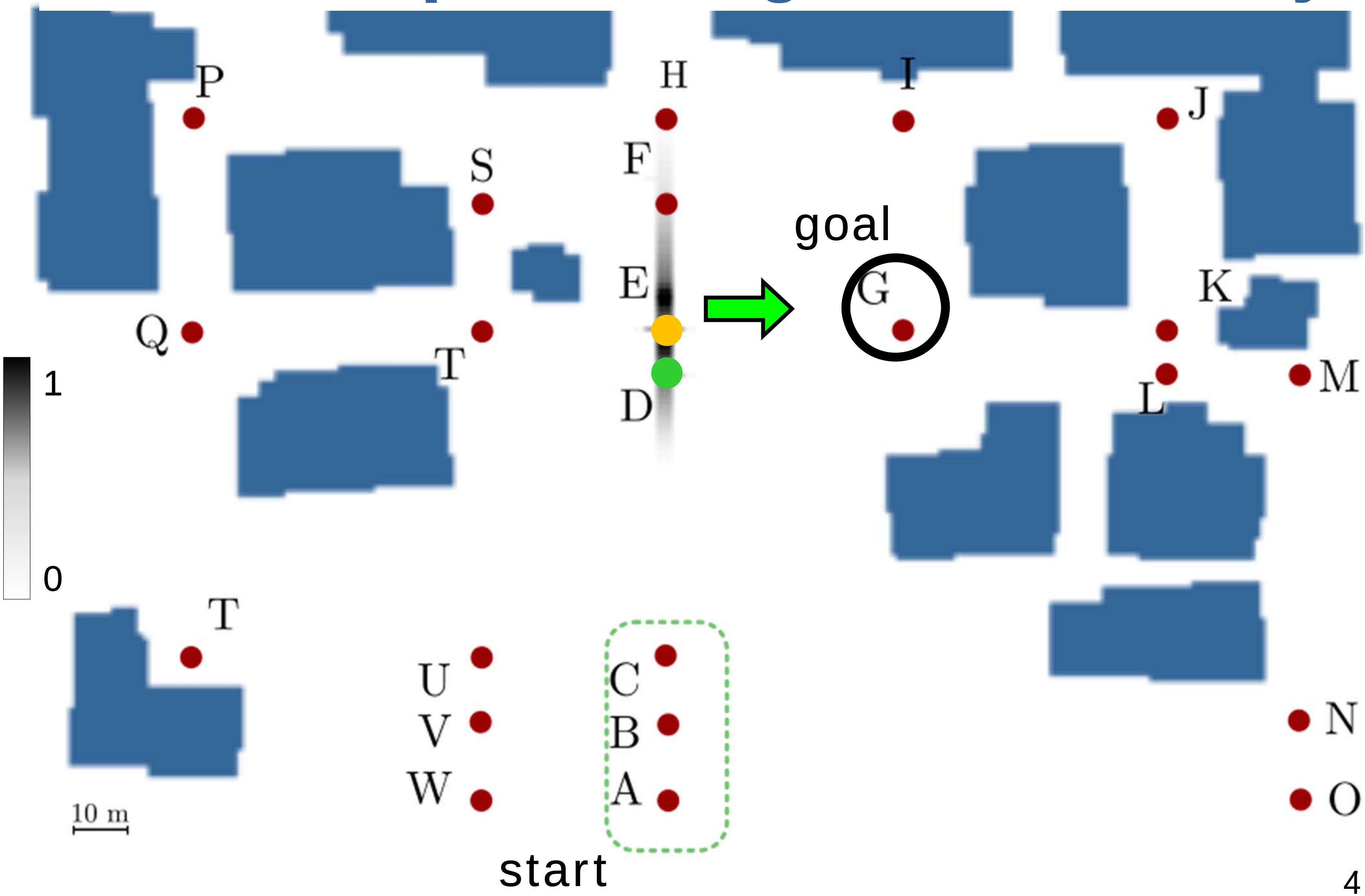

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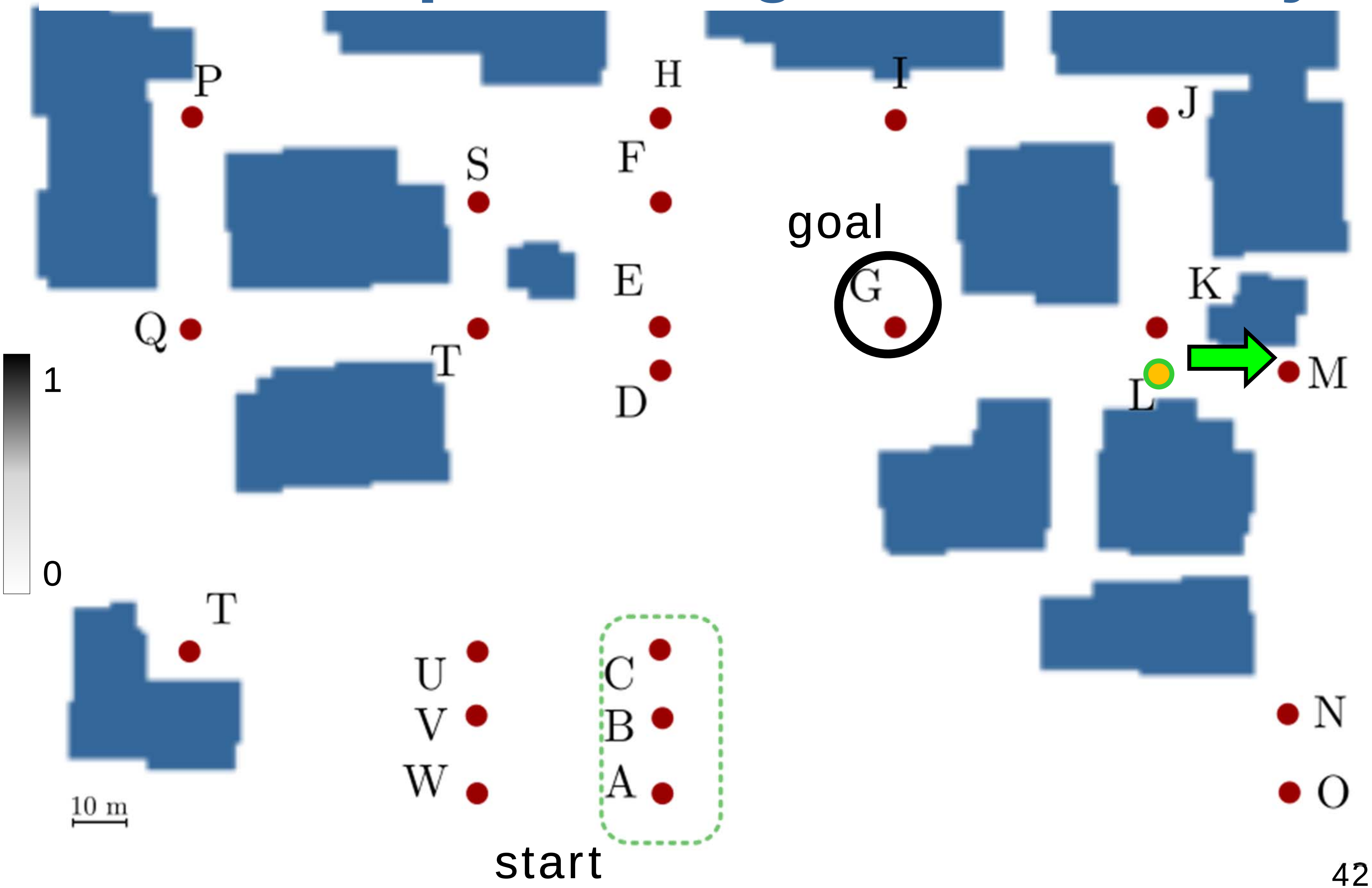

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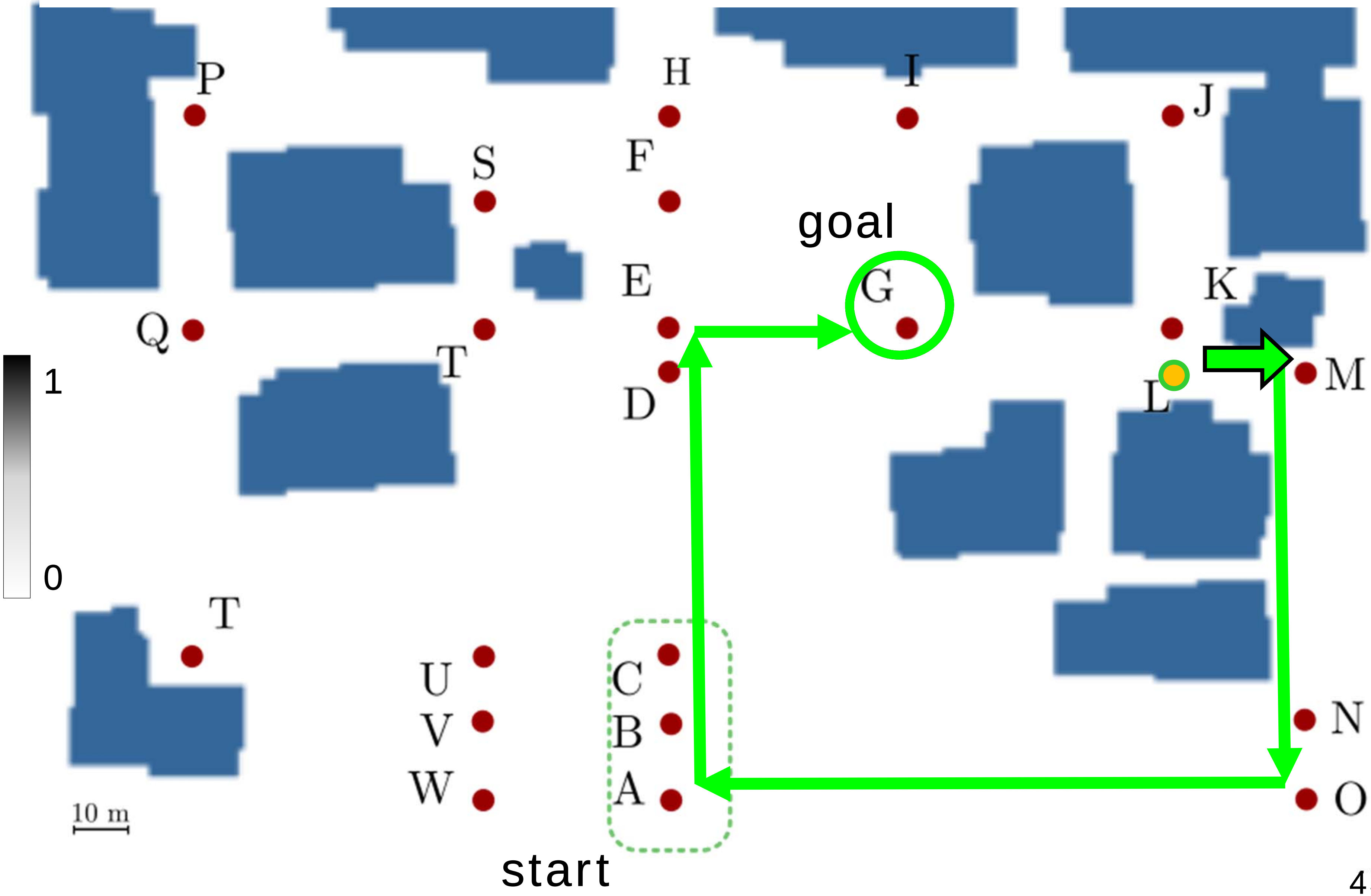
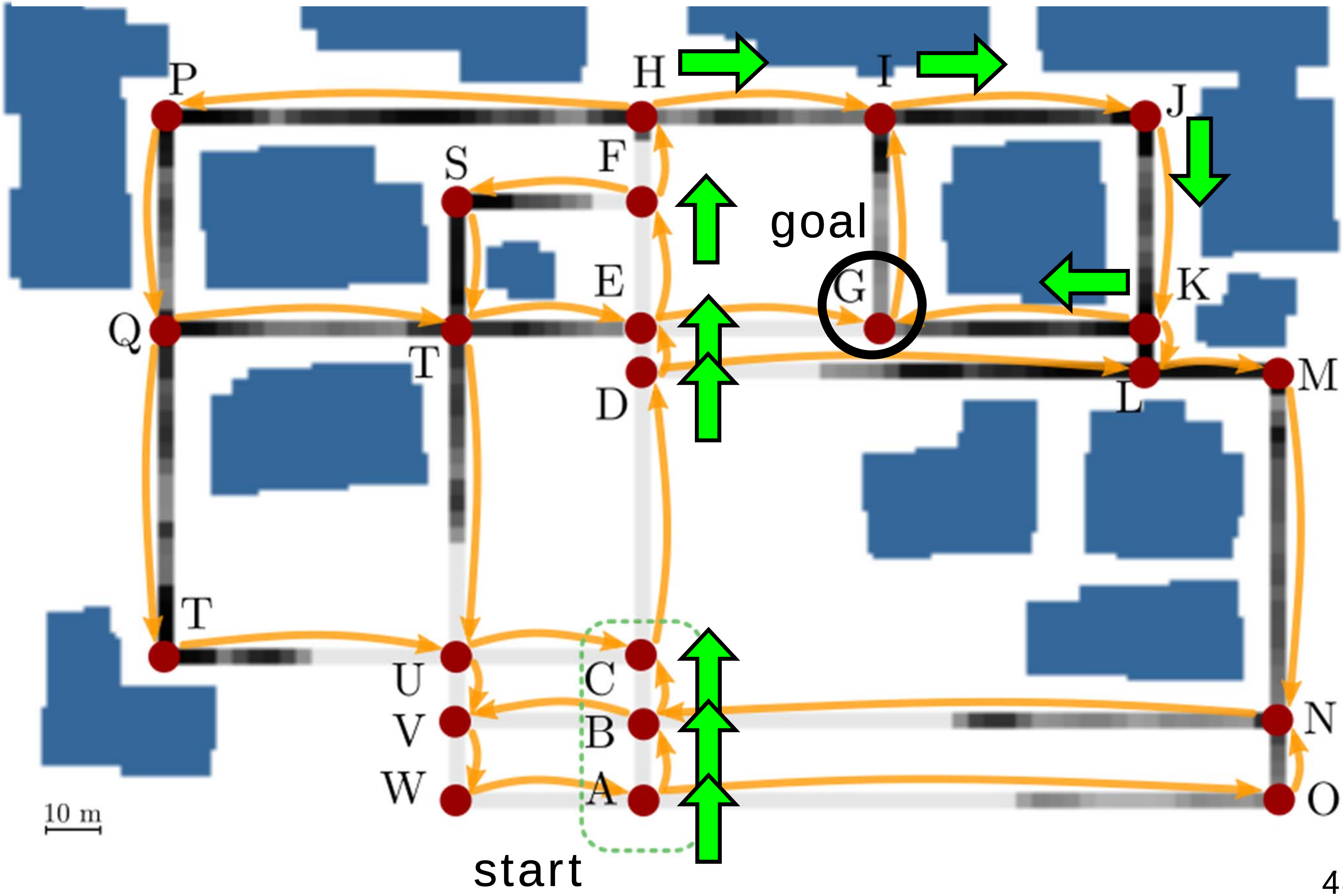


Safest path policy



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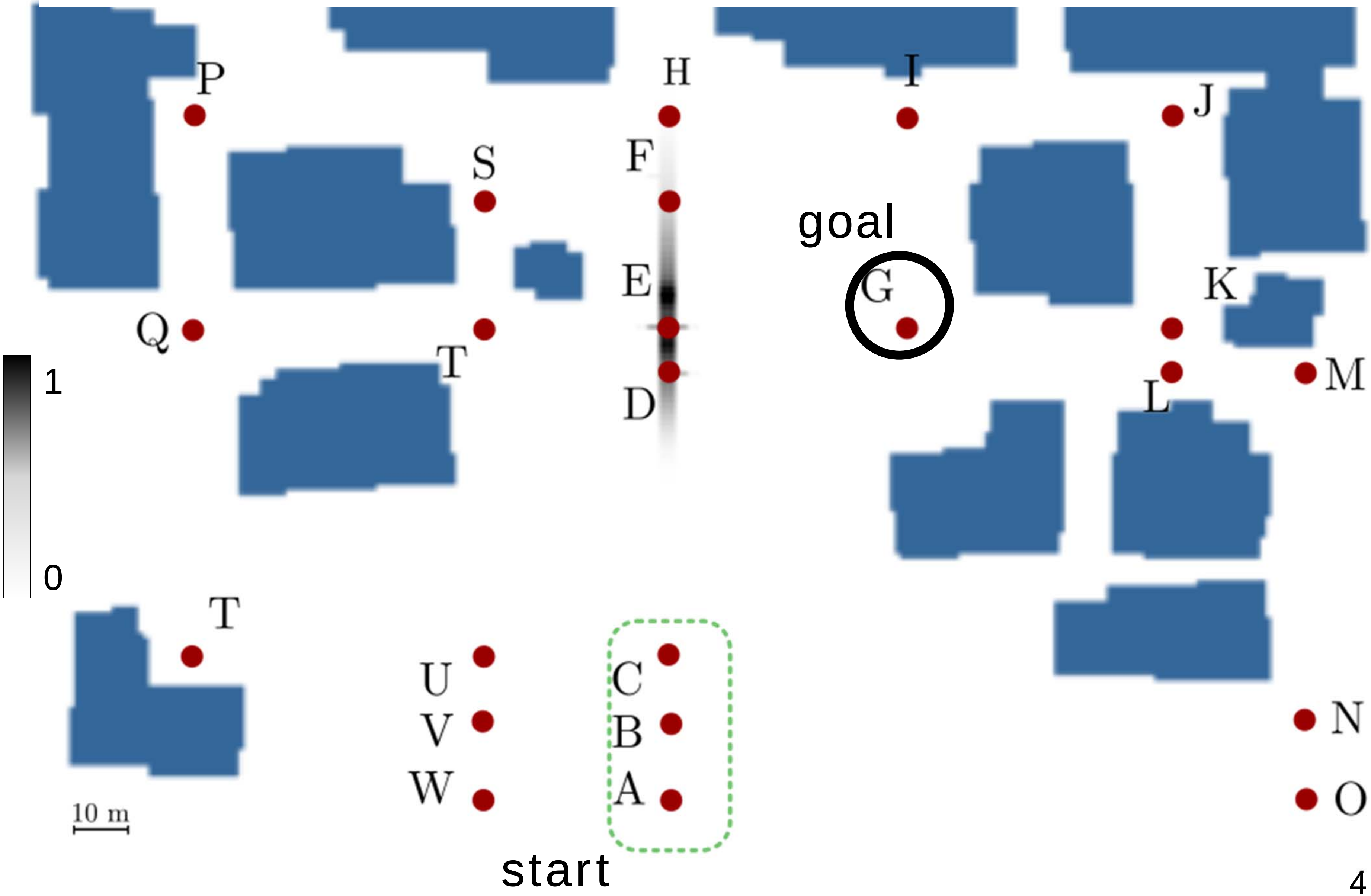

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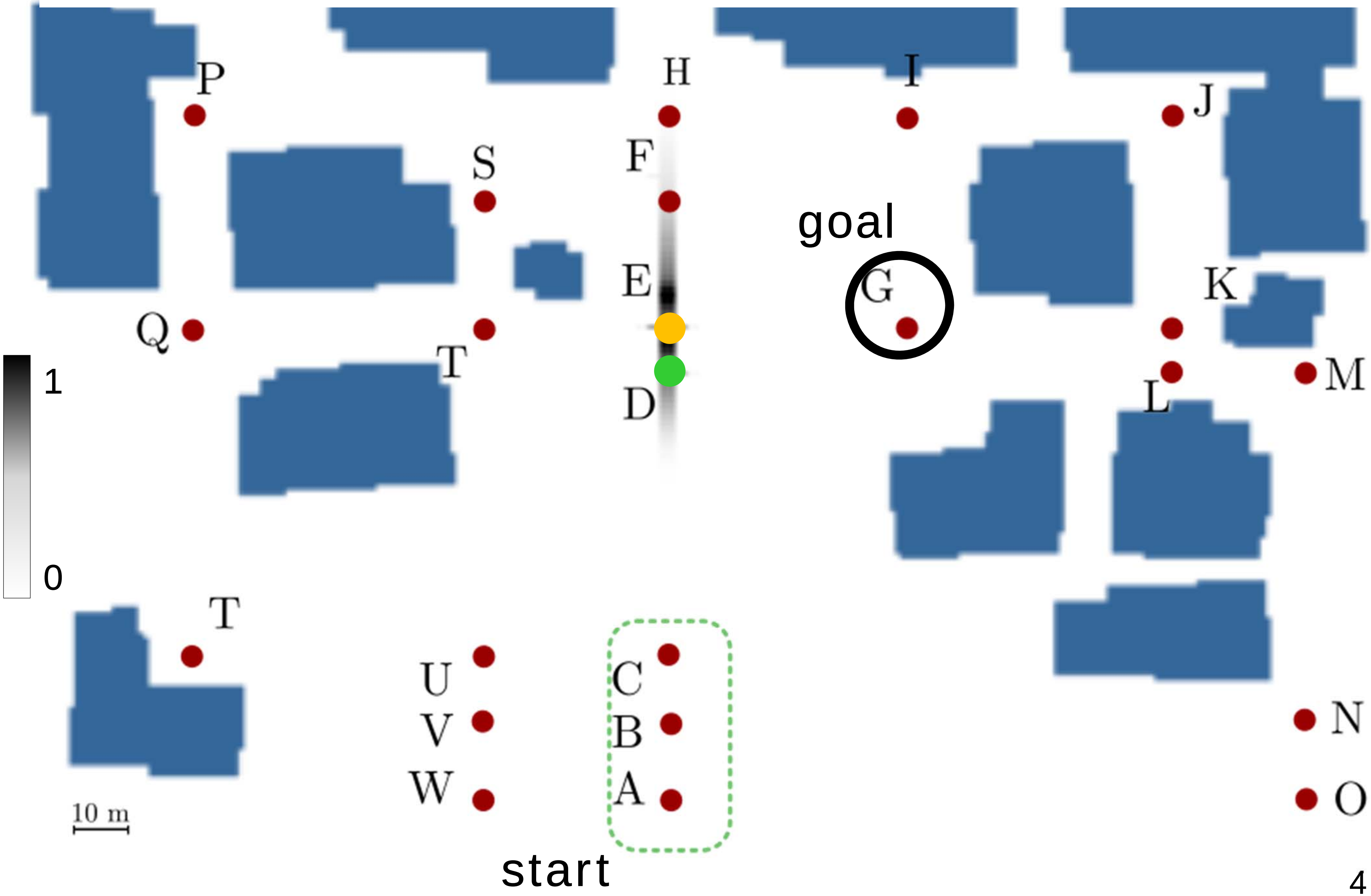

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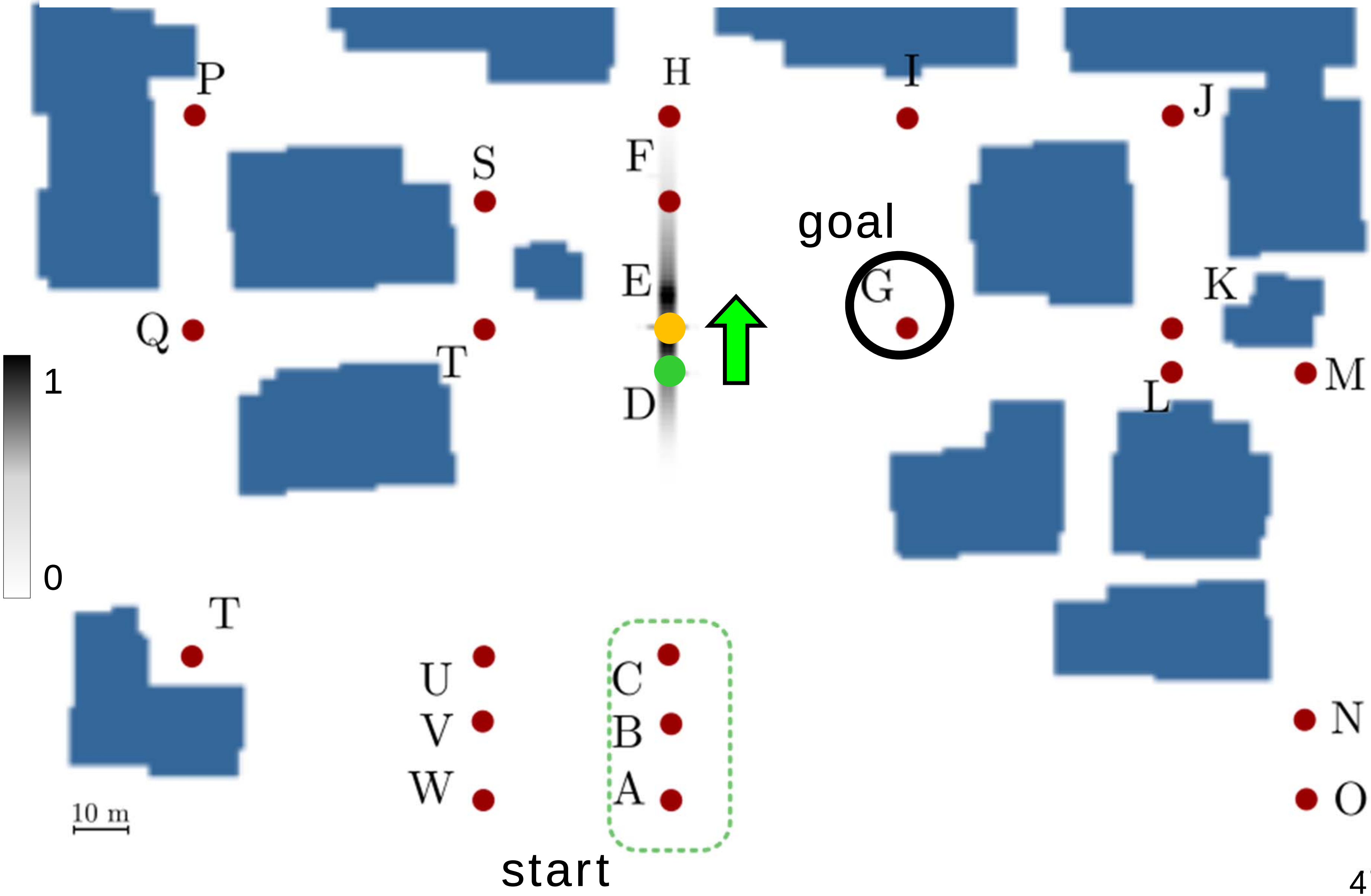

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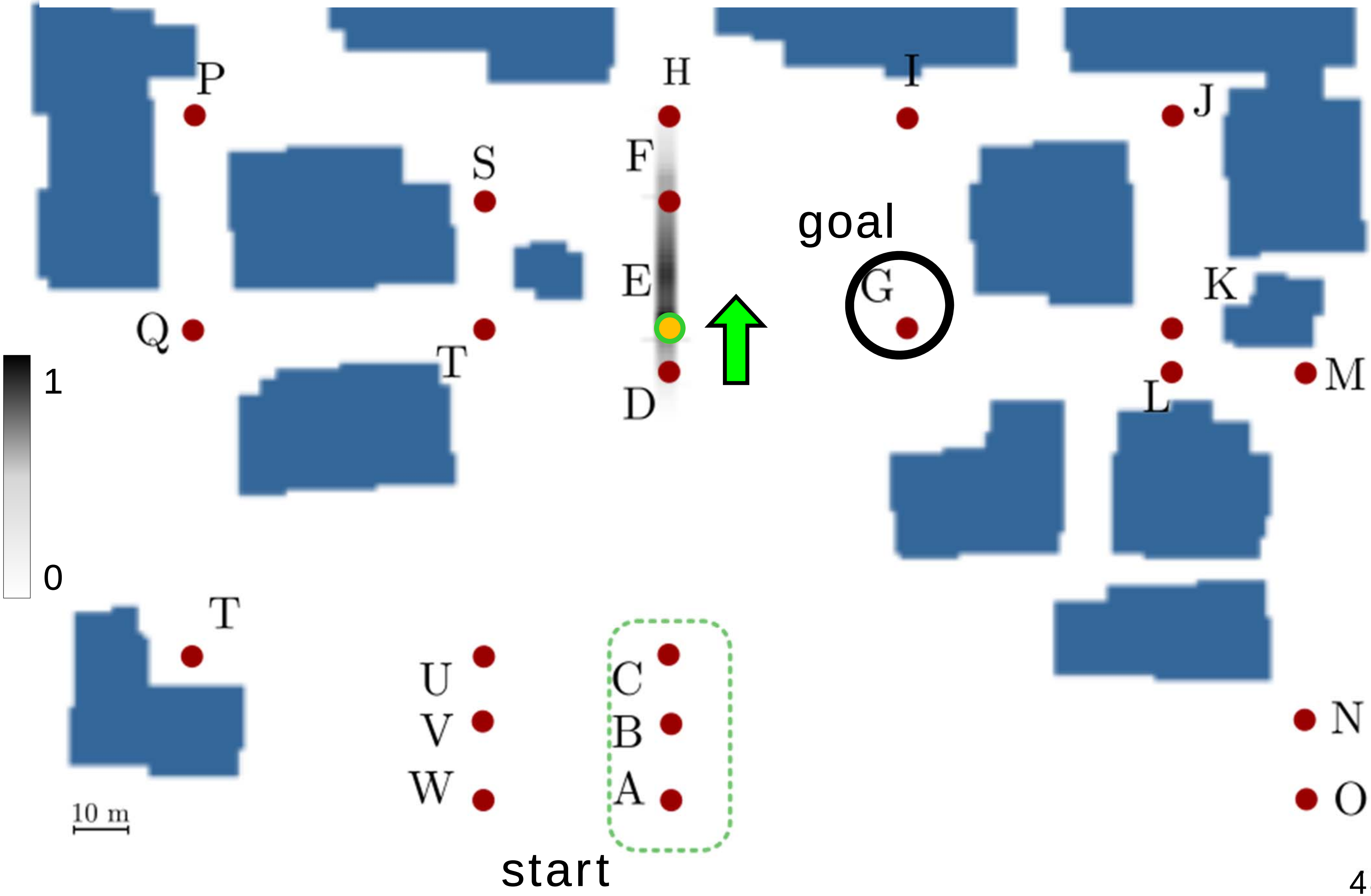

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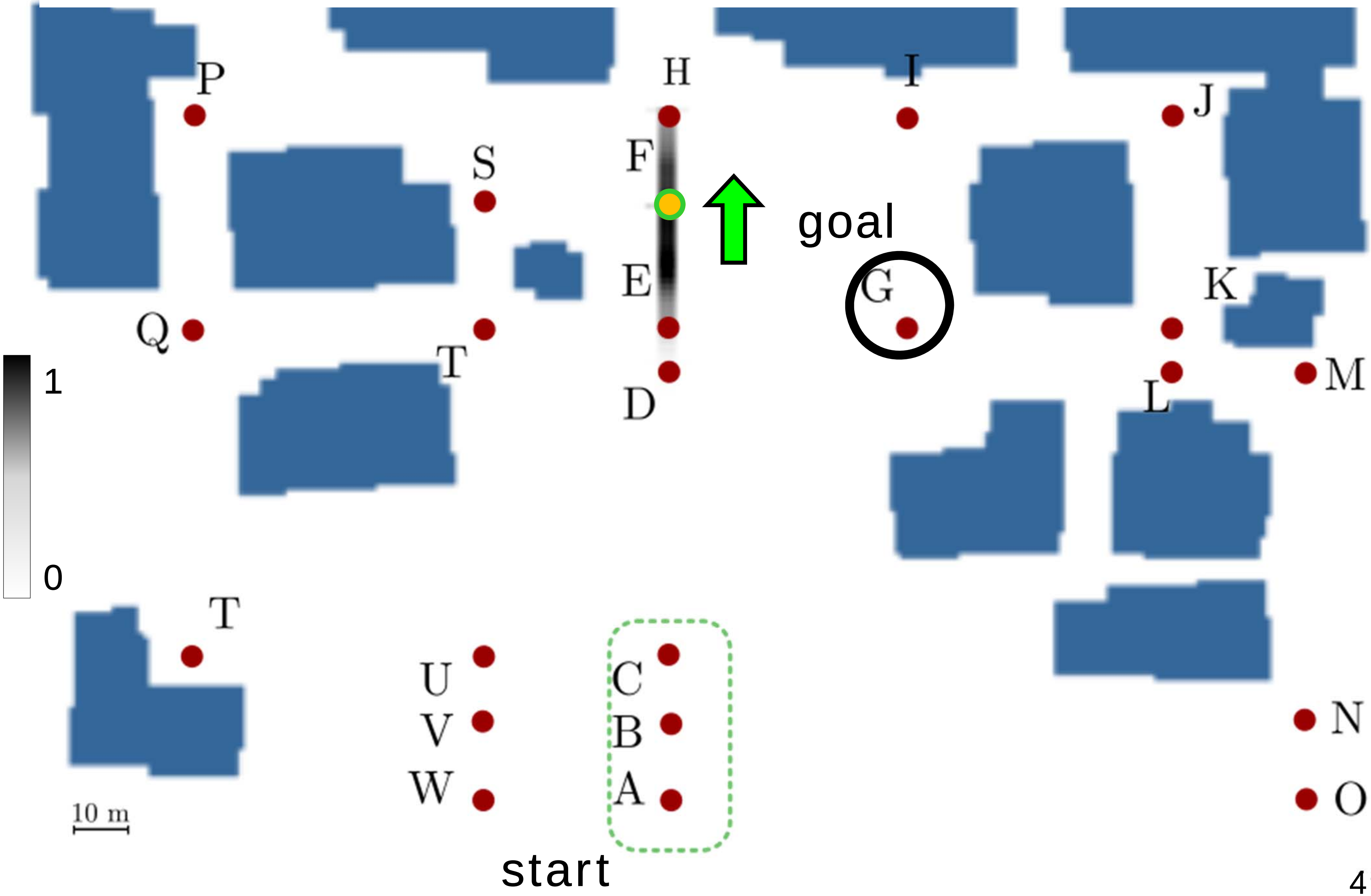

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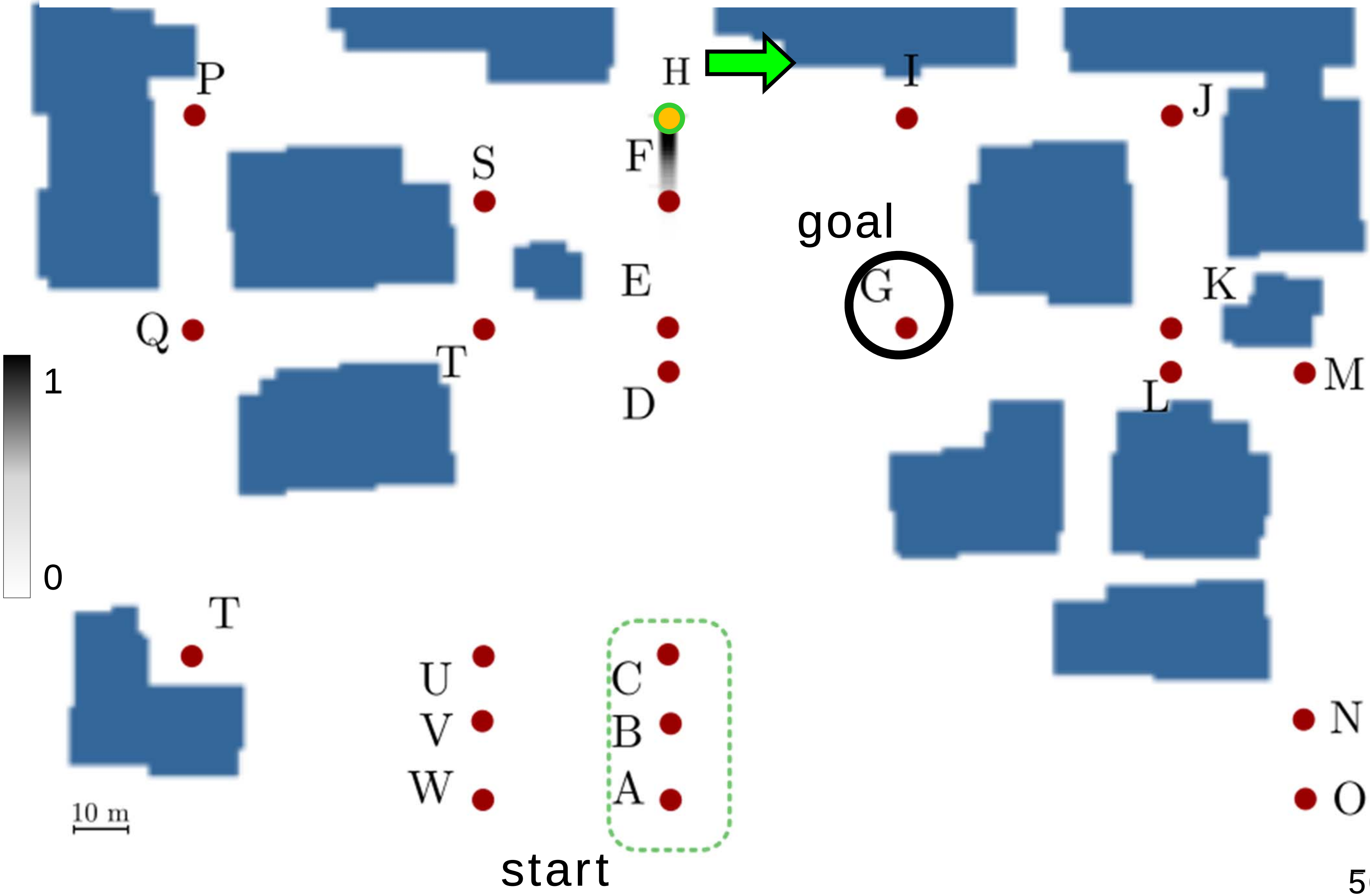

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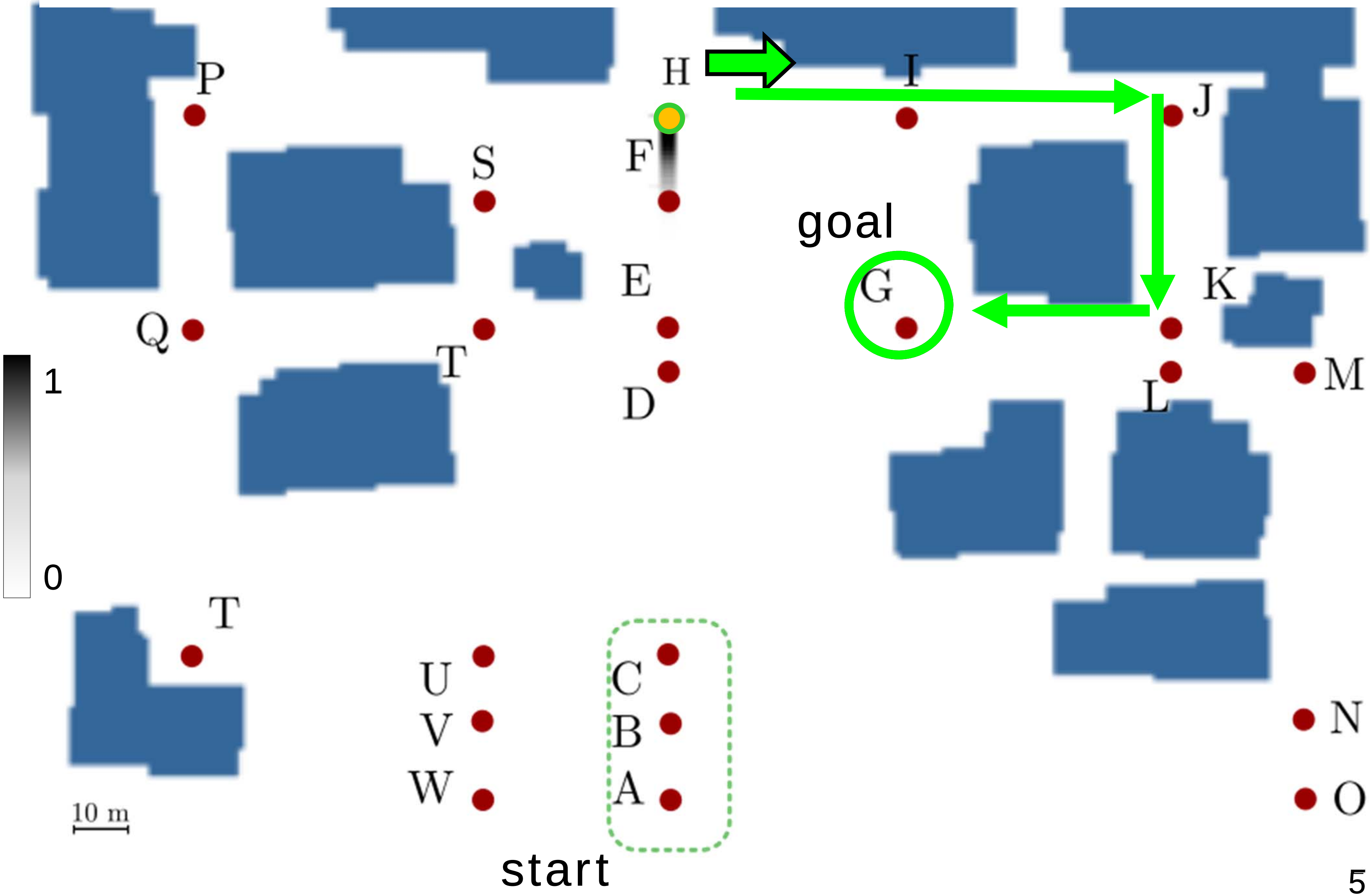

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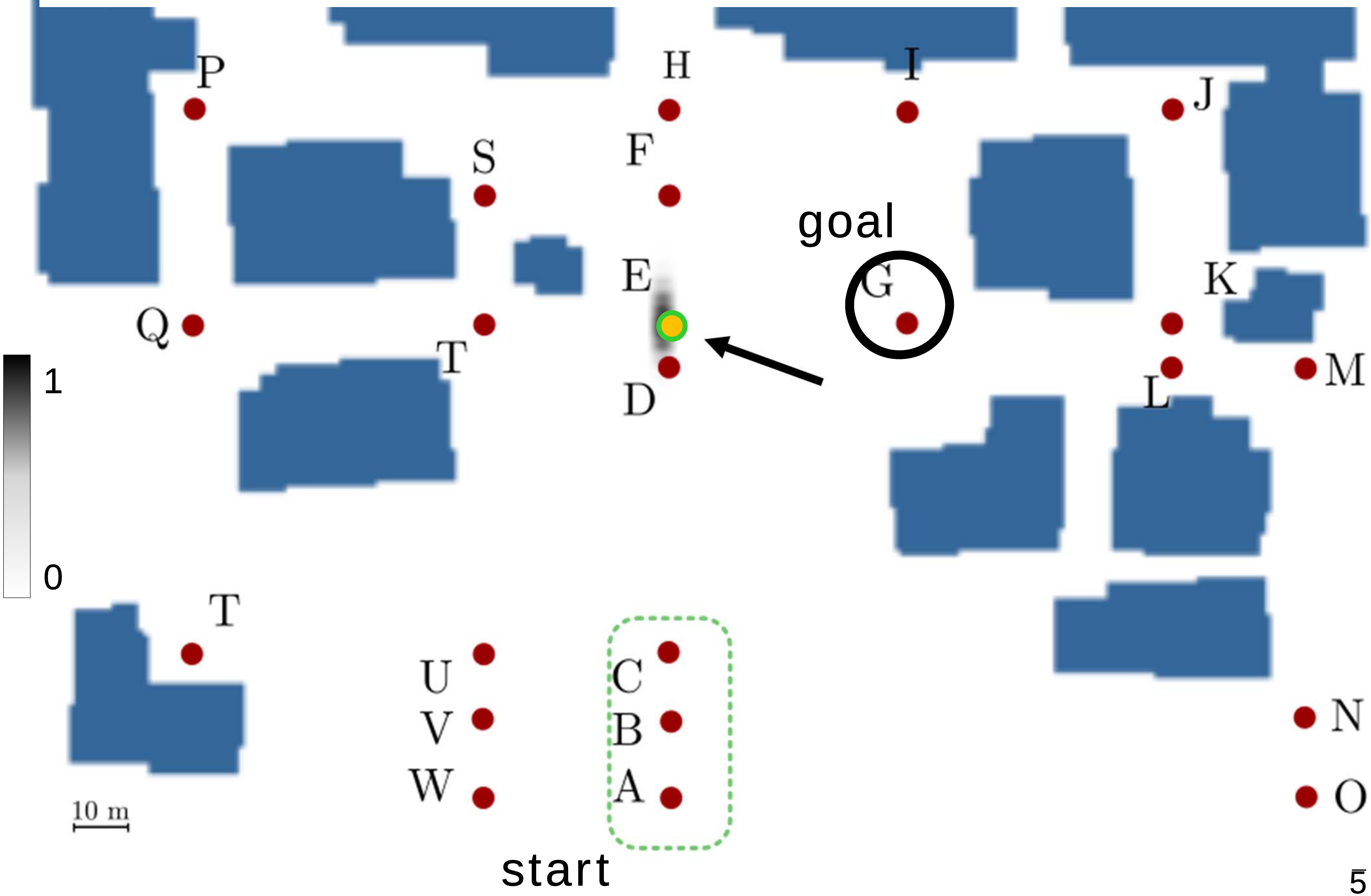

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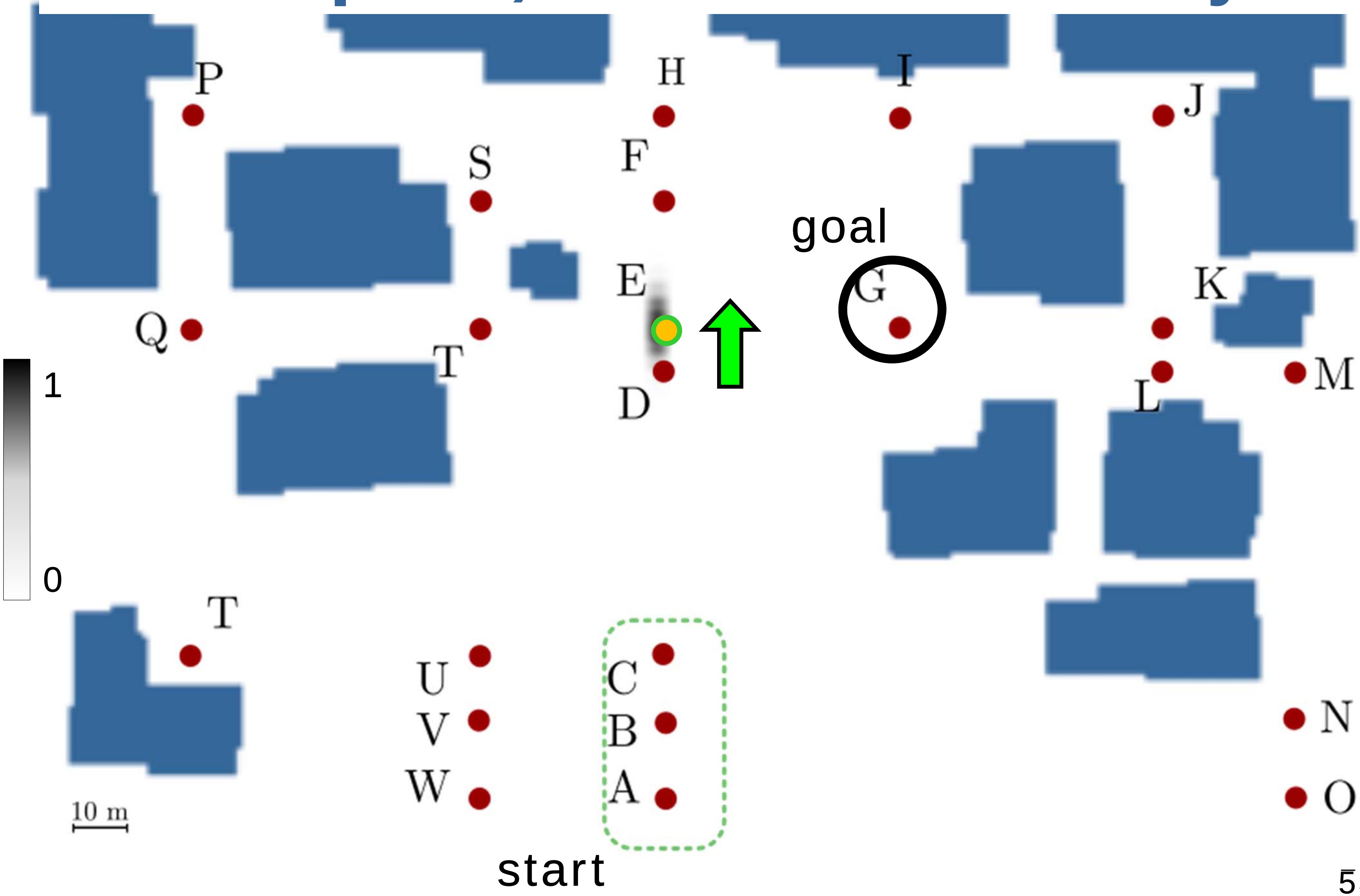

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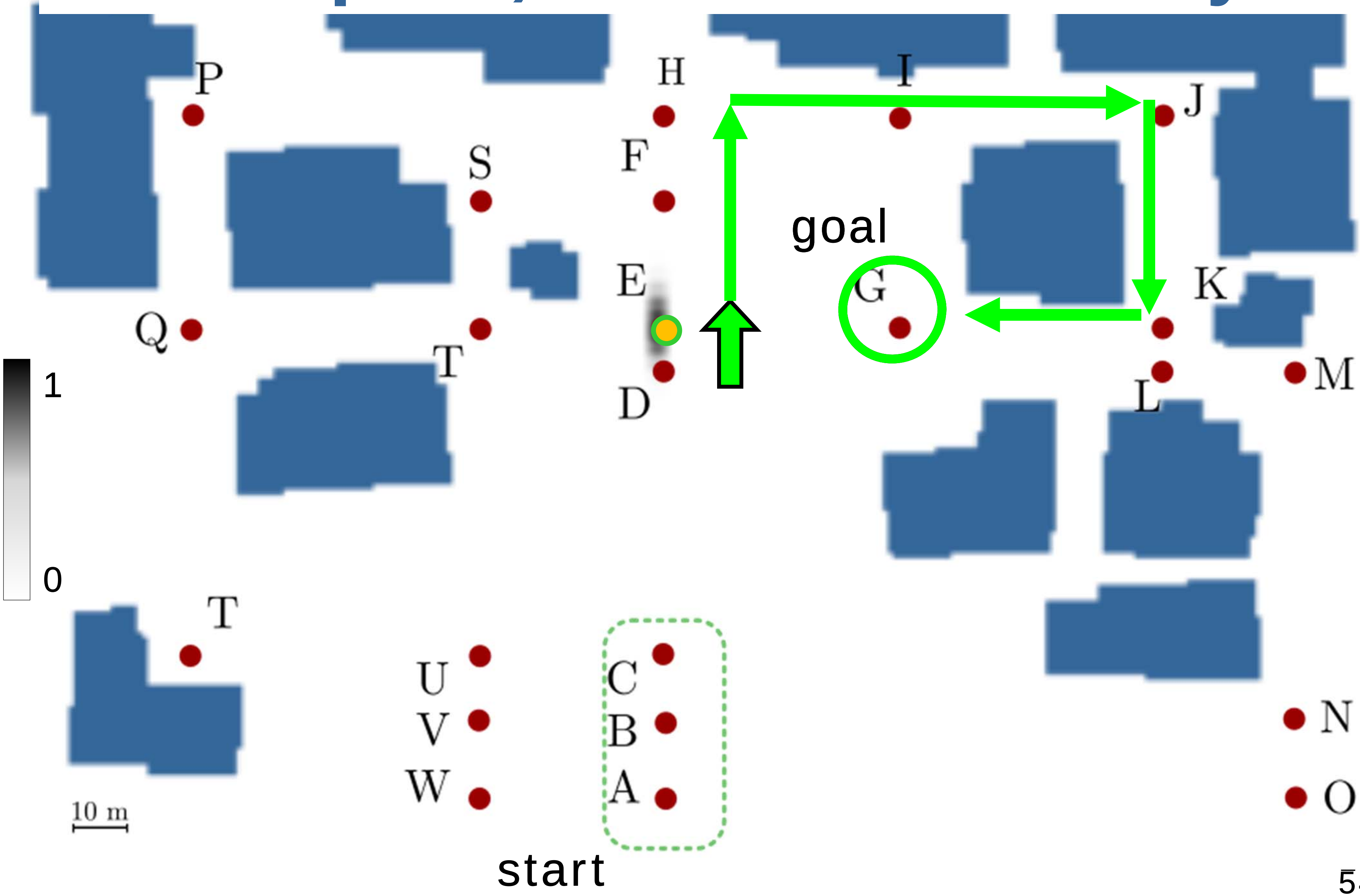
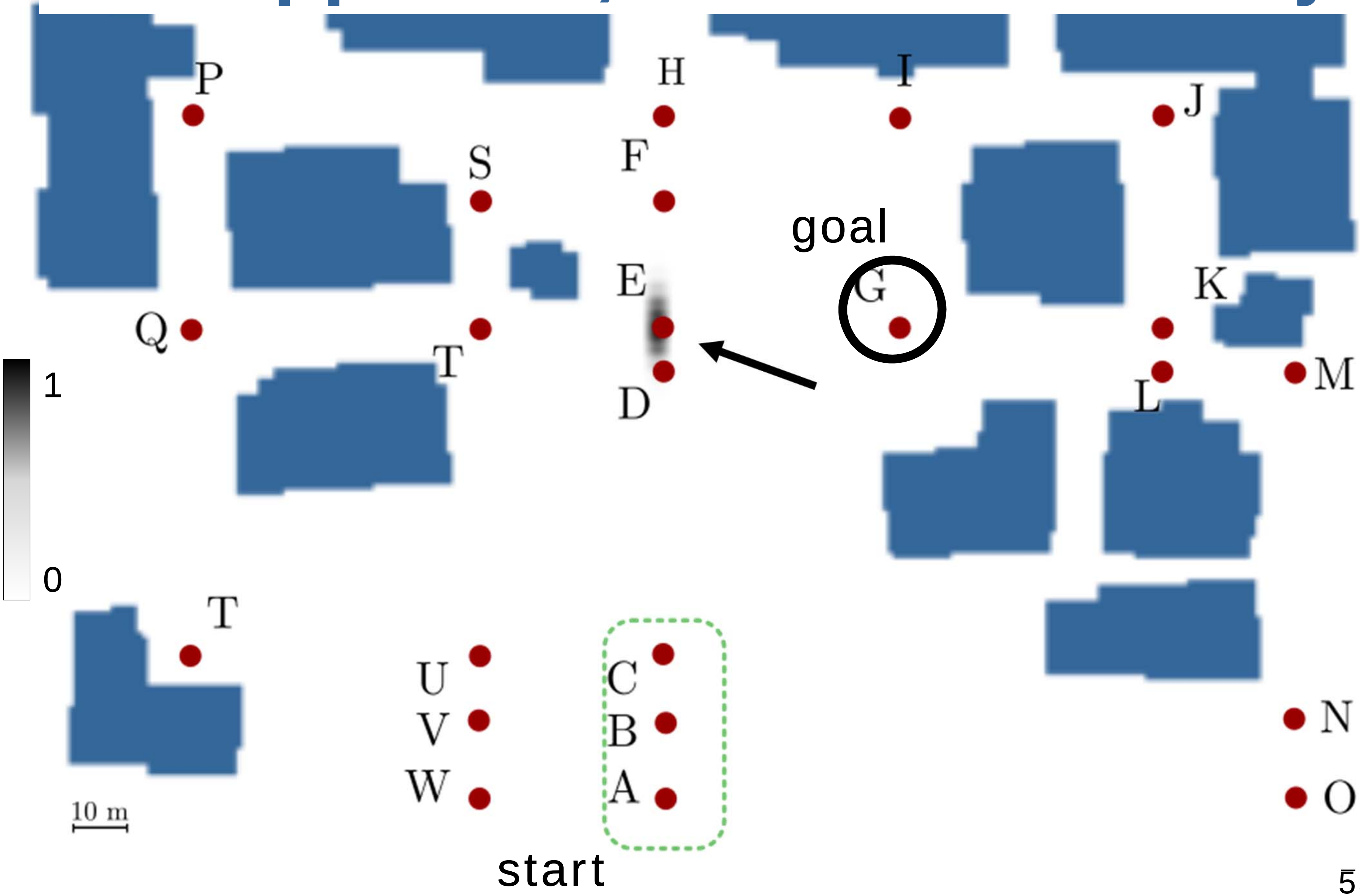


Our approach, small uncertainty



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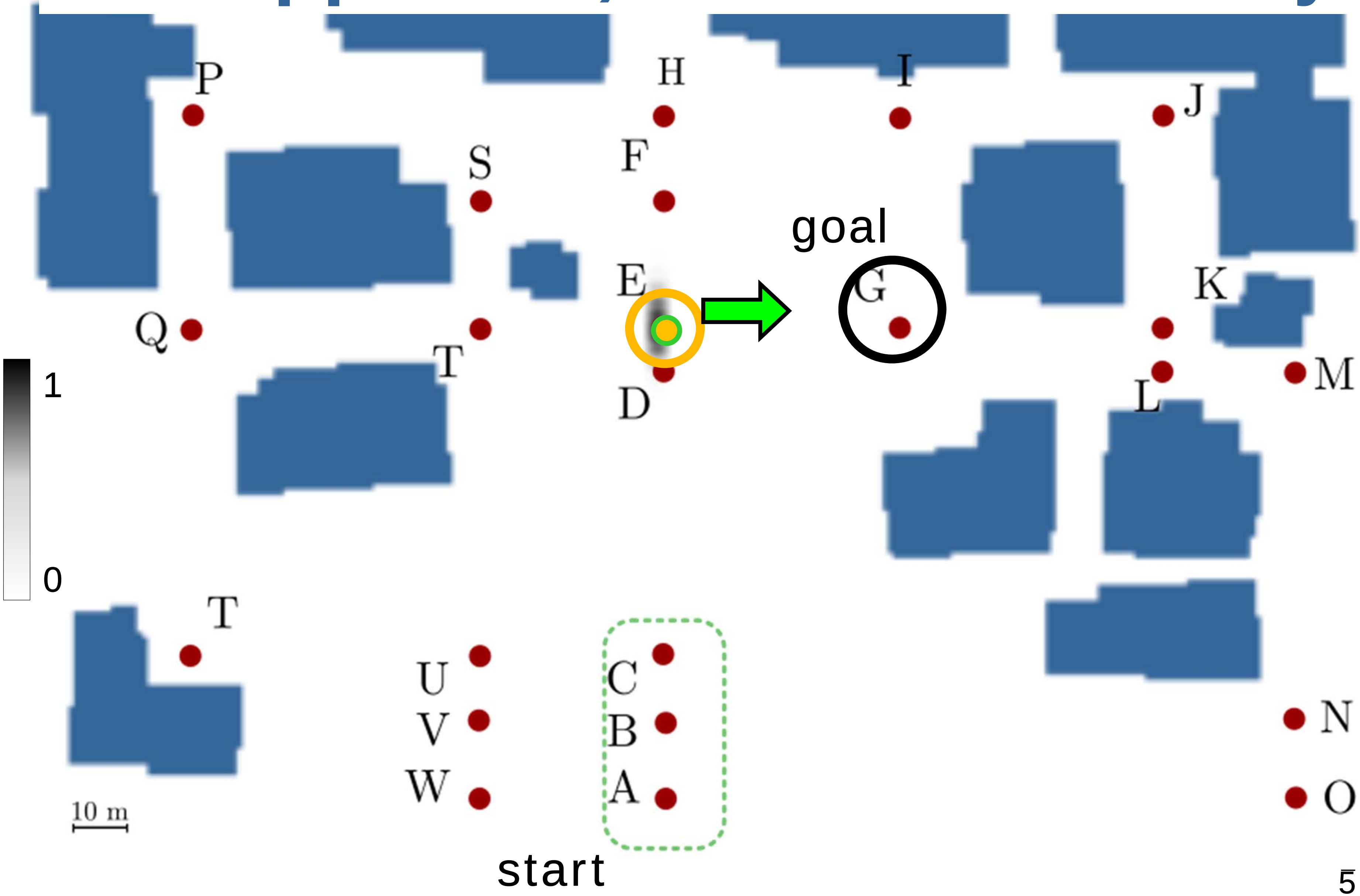

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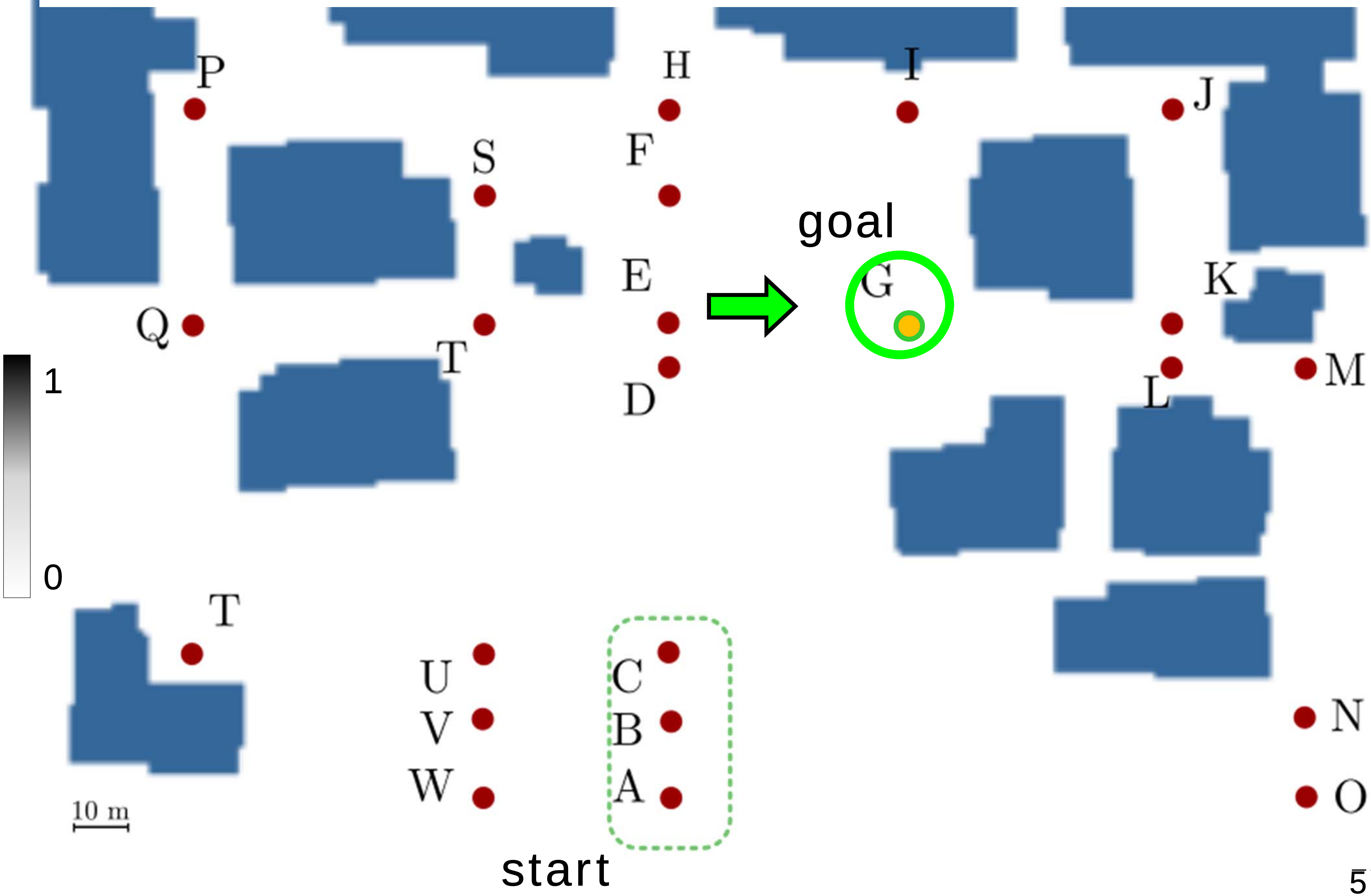

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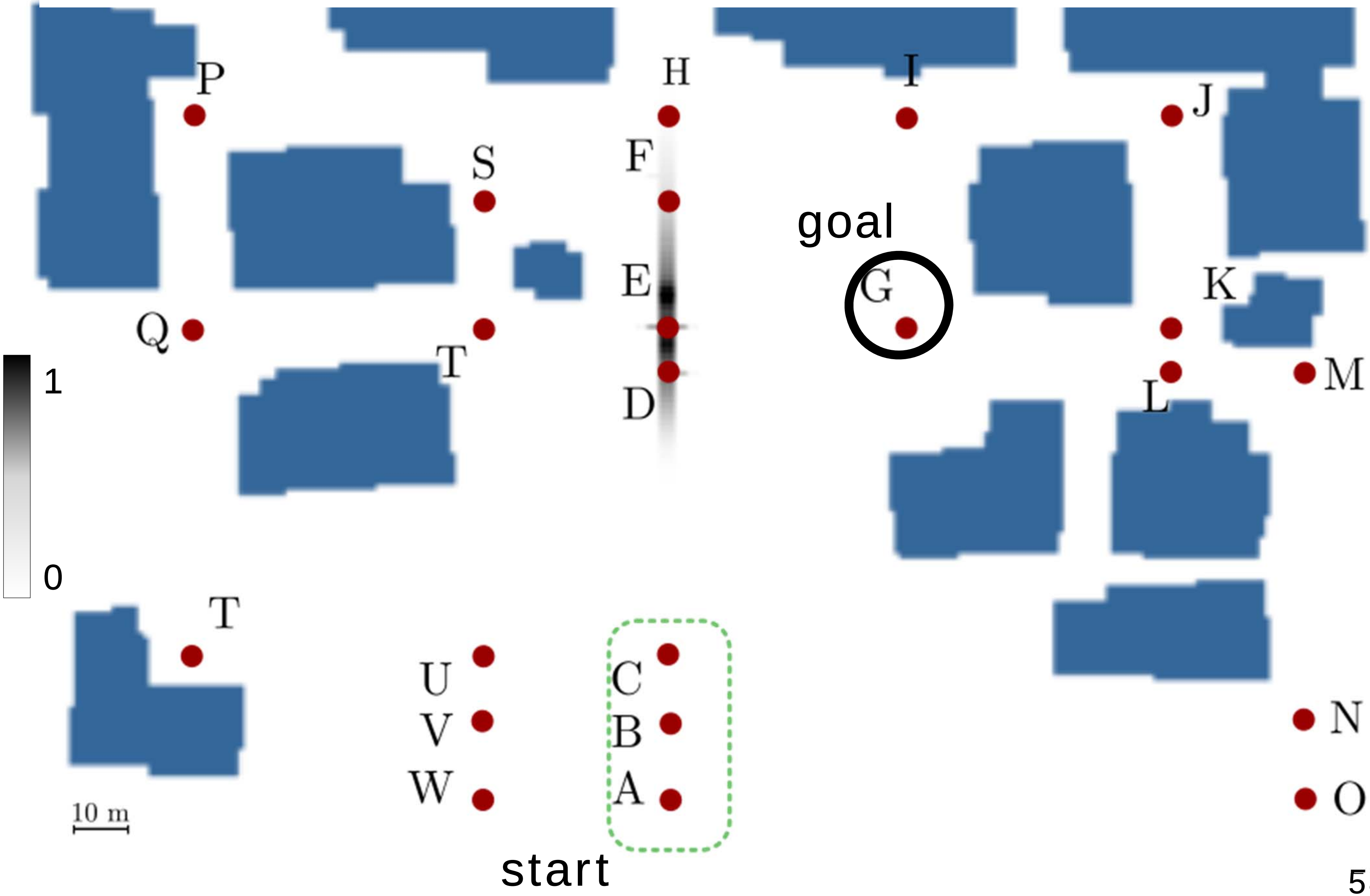

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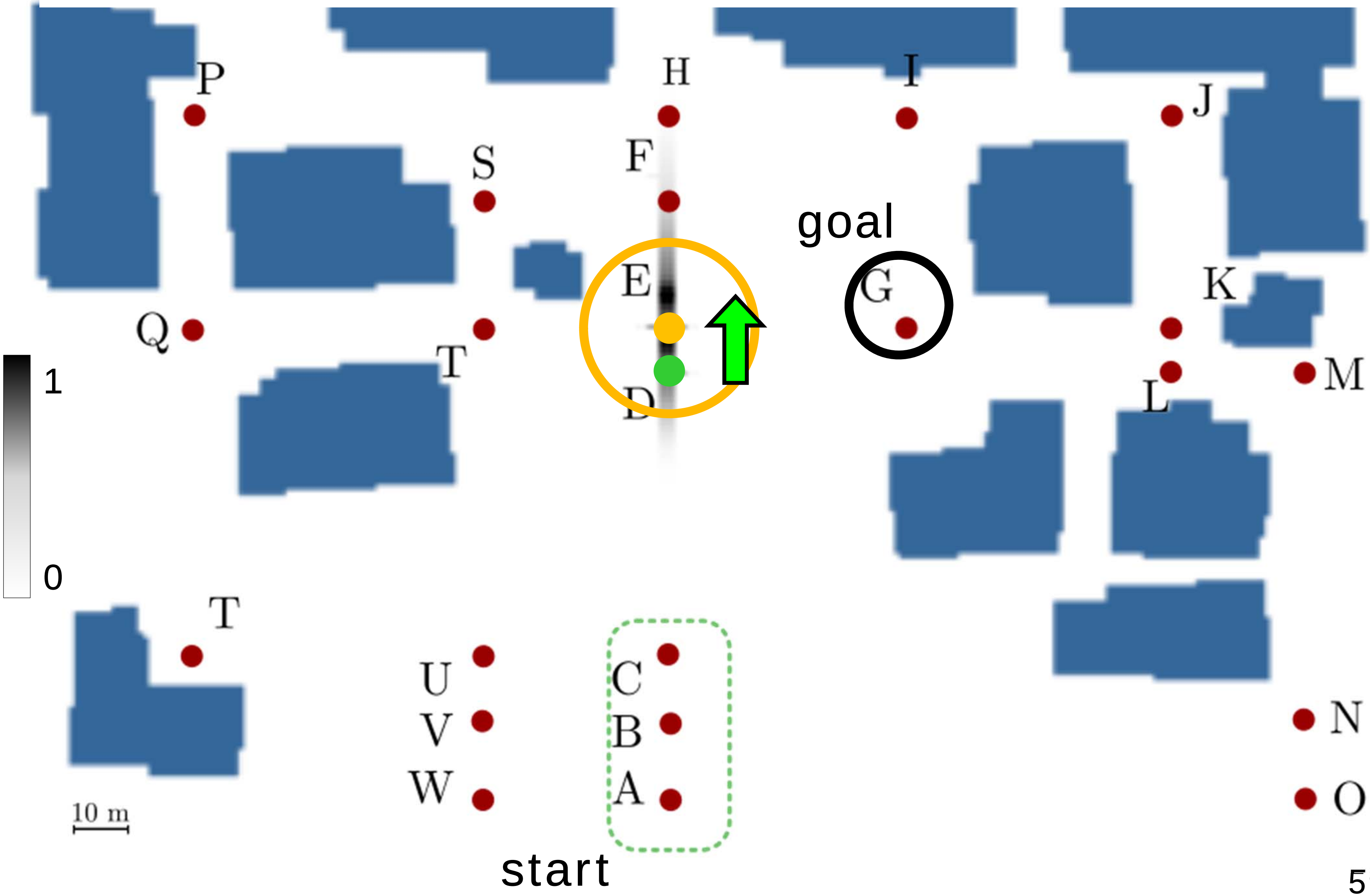

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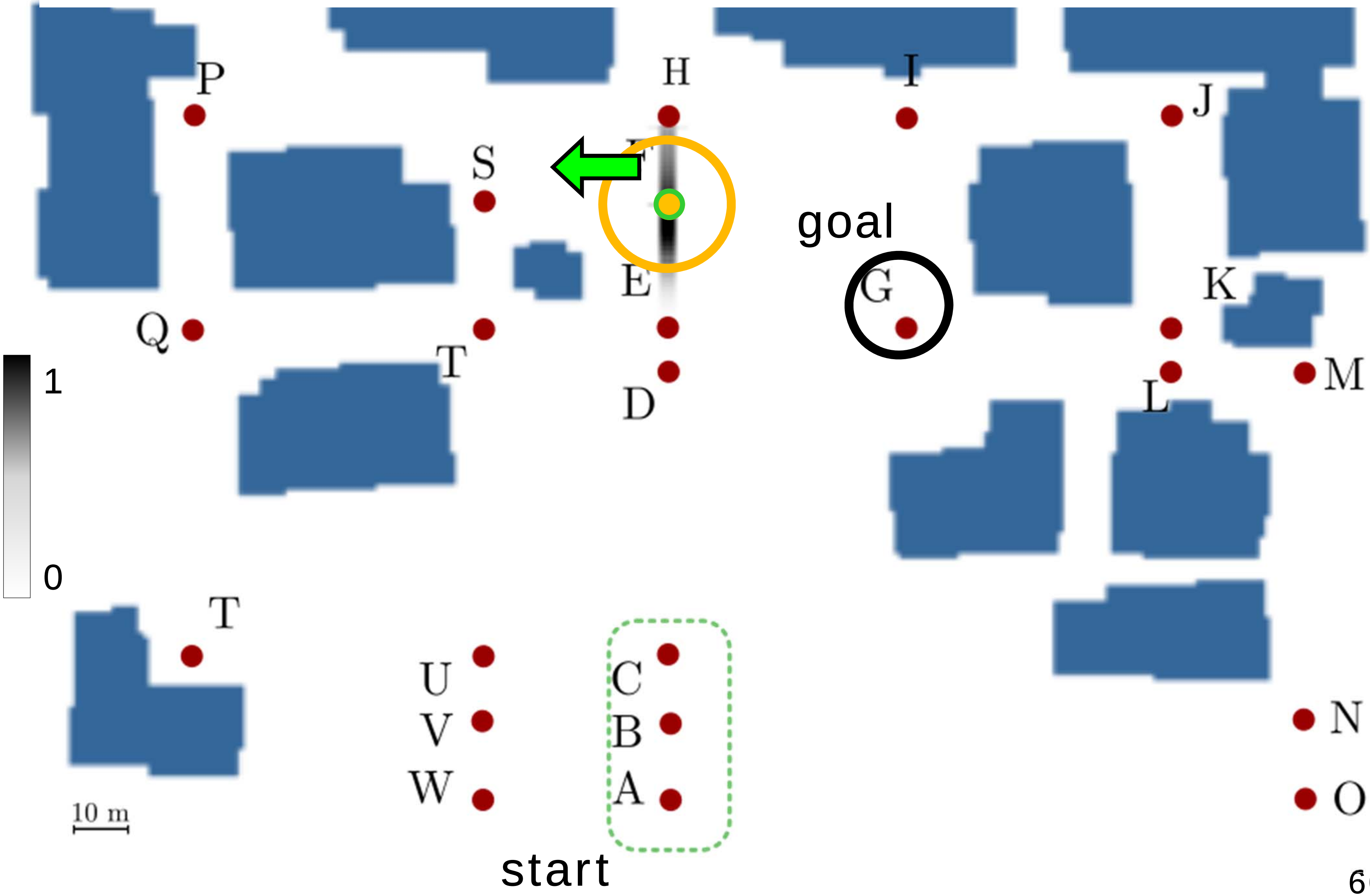

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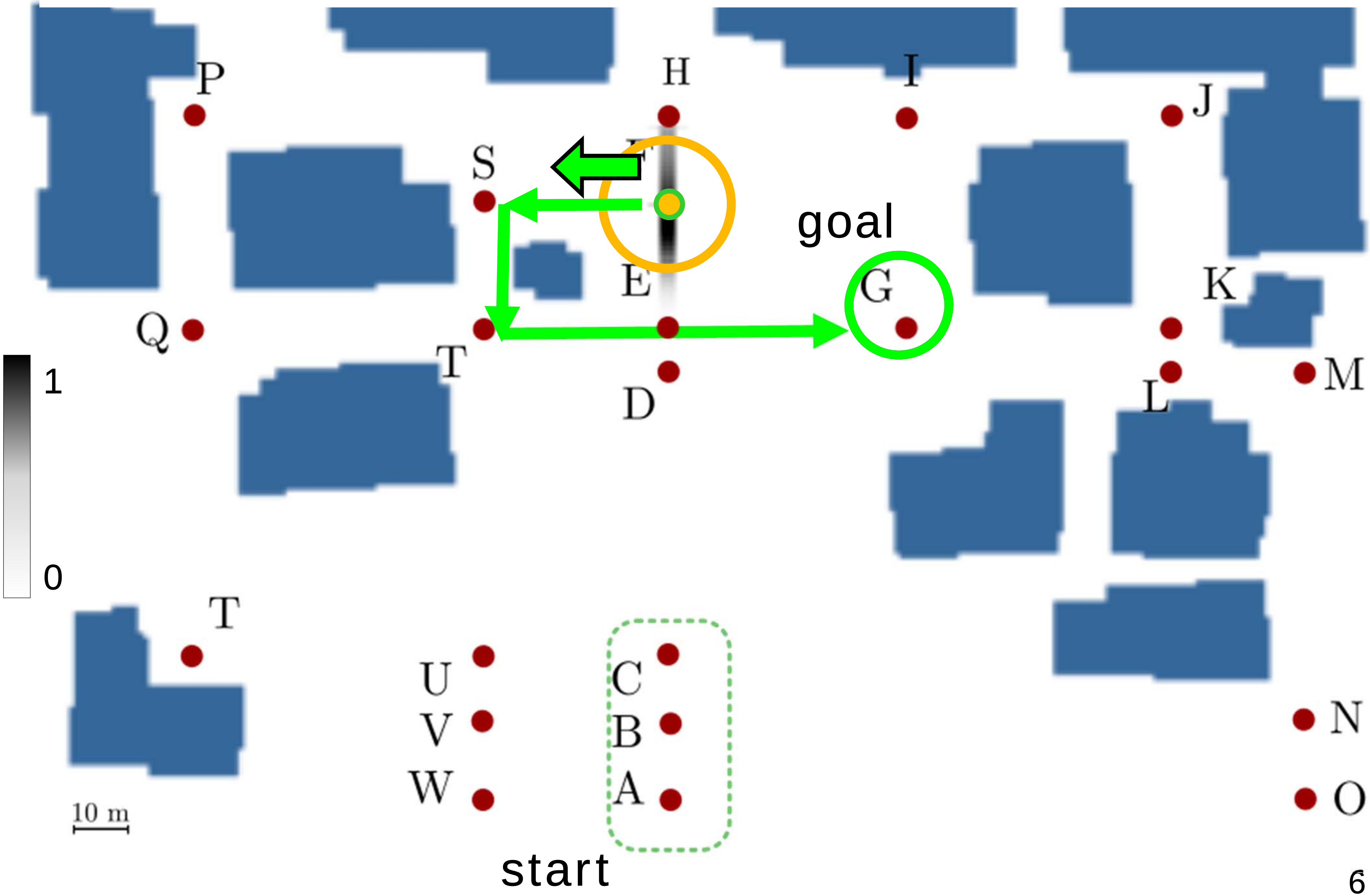

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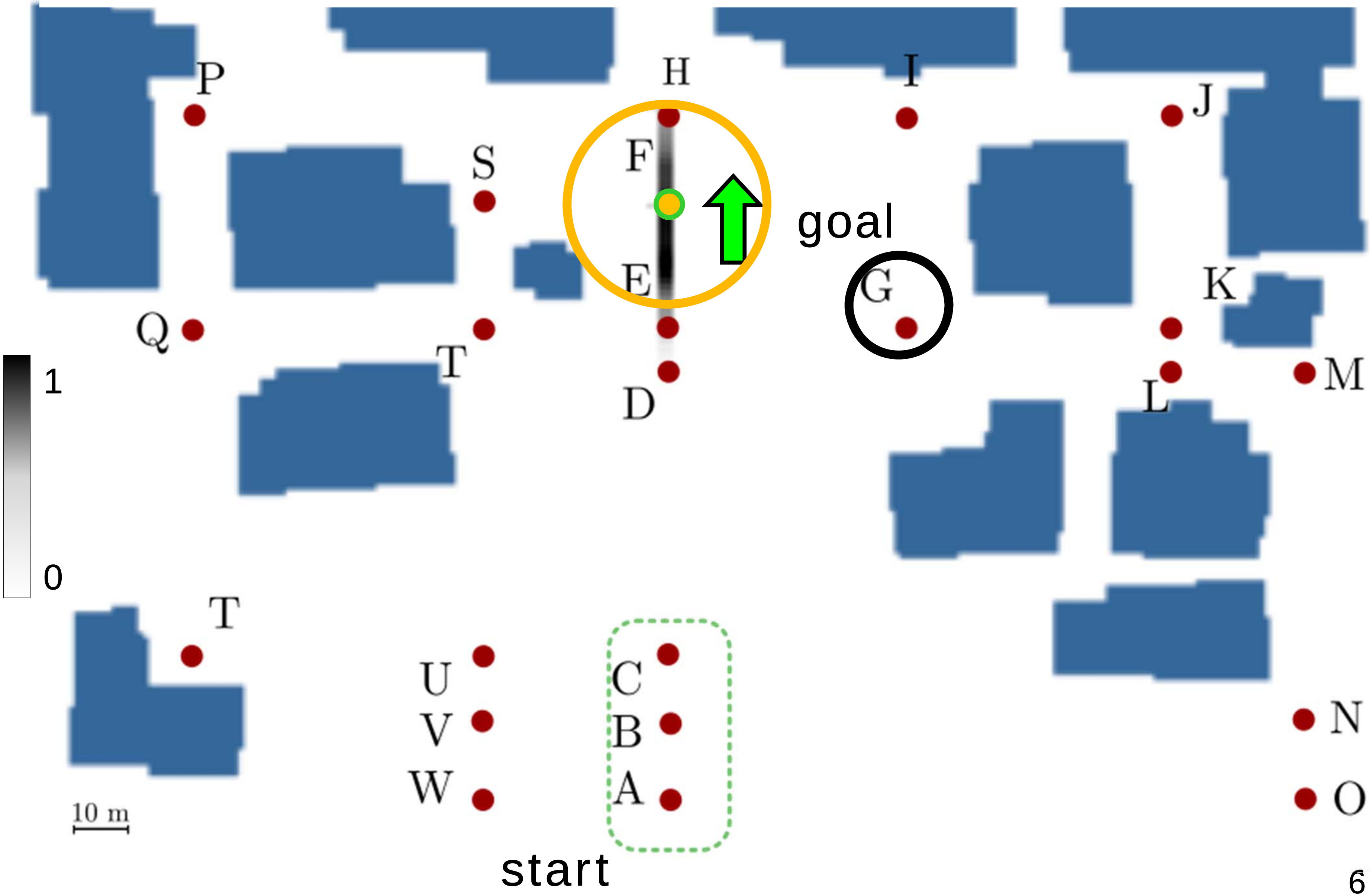

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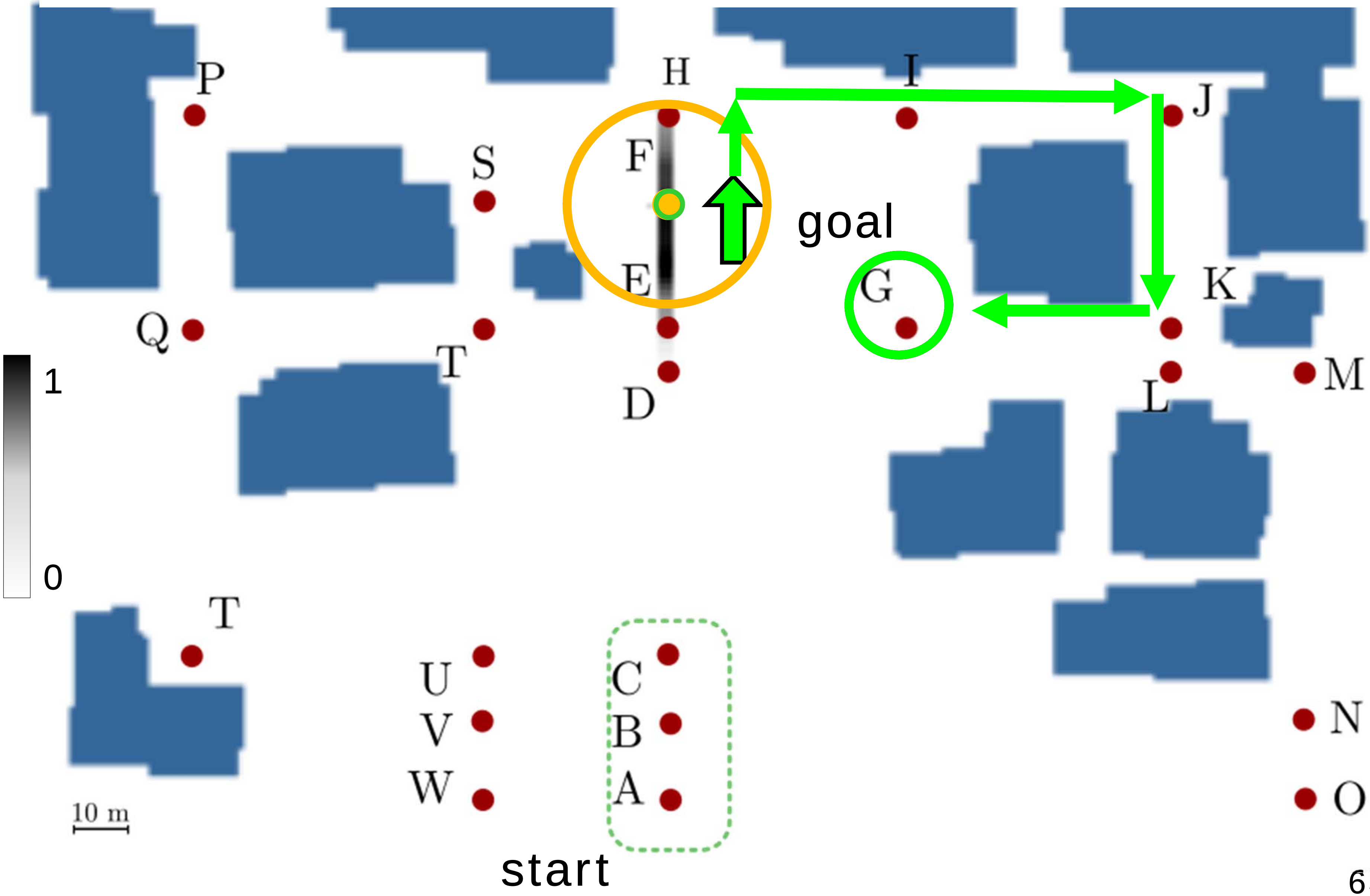
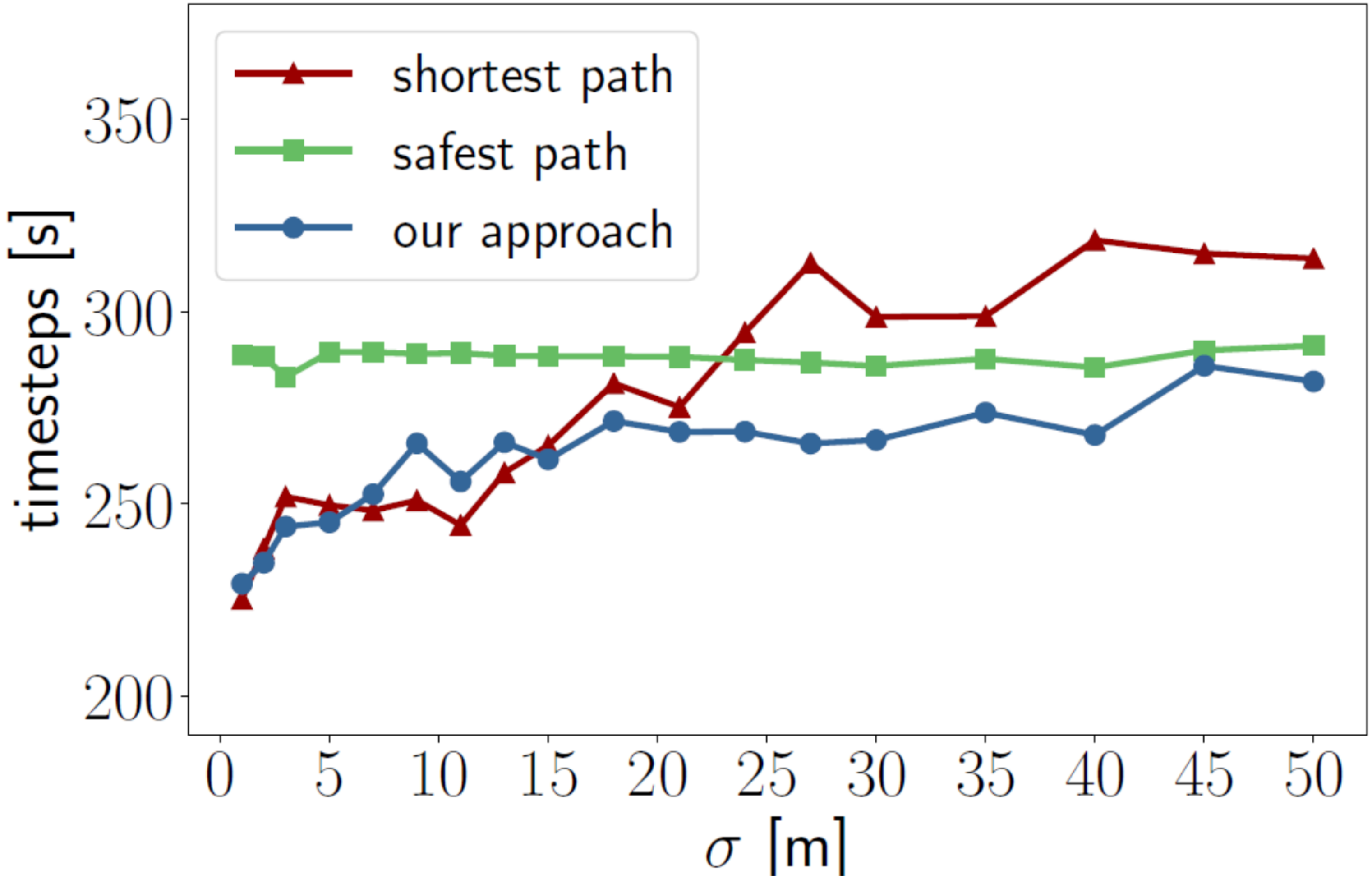


Shorter avg. travel time than the shortest and safest path policy



Summary

- Planning on road networks explicitly considering **position uncertainty**
- **Augmented-MDP** approximates efficiently POMDP
- **Localization prior** estimates belief propagation through the network
- Policy **trades-off safety and travel time** given the current belief

Thank you for your attention