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Planning with Conflict-Based Search

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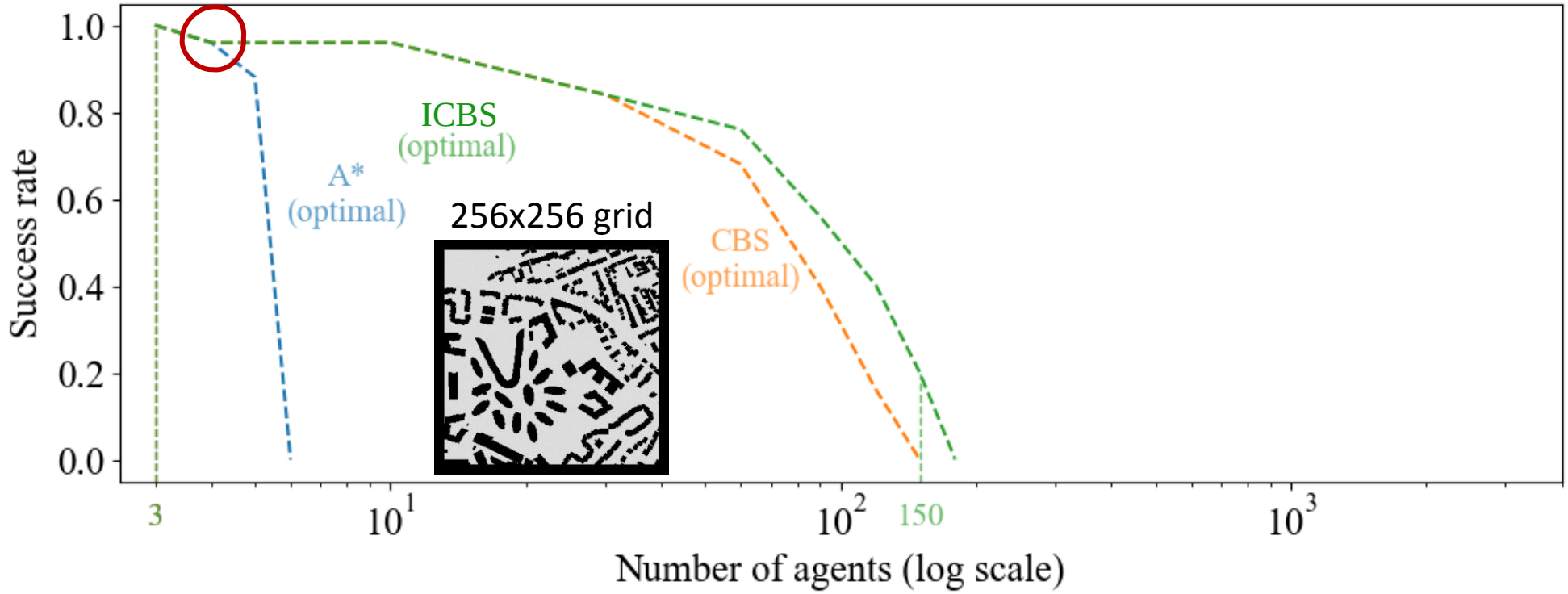
A* and Conflict-Based Search (CBS)



Runtime limit: 1 minute

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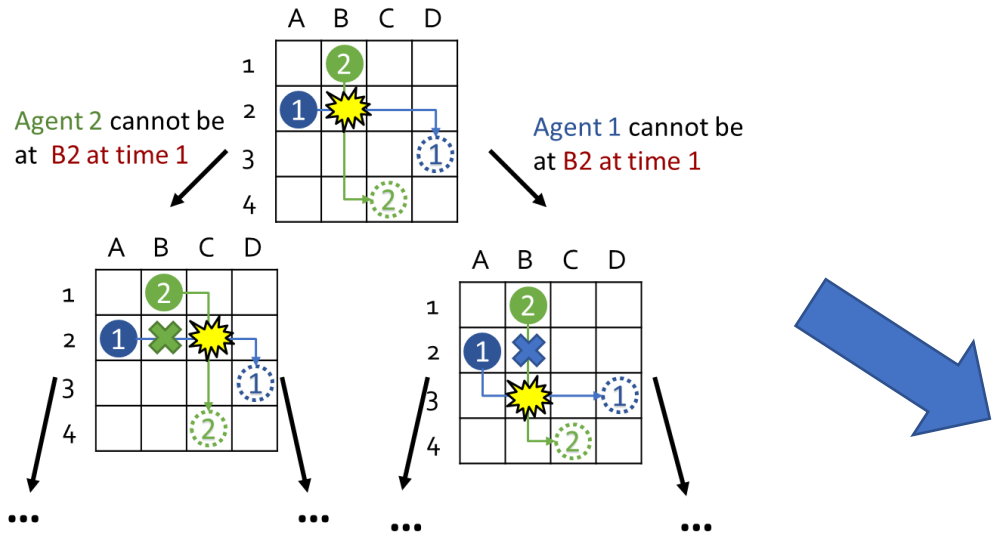
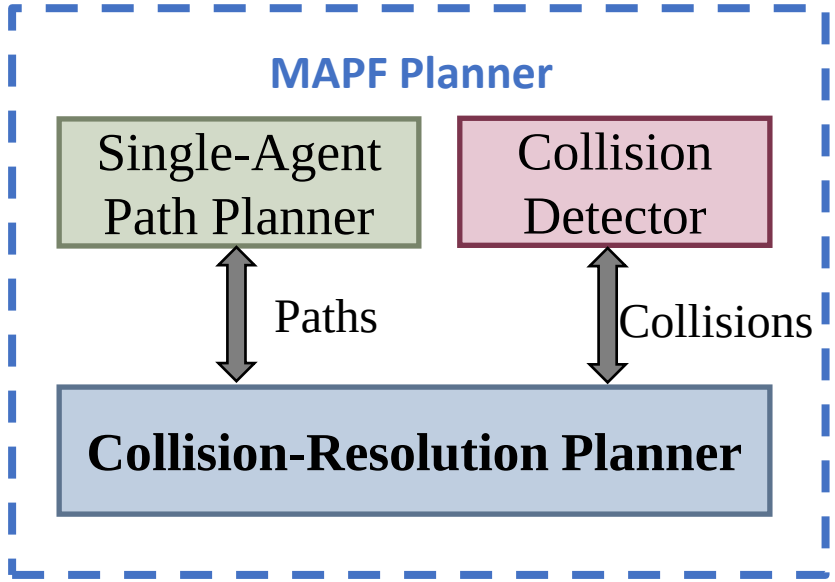
Conflict-Based Search (CBS)





How to resolve collisions?

How to choose nodes?

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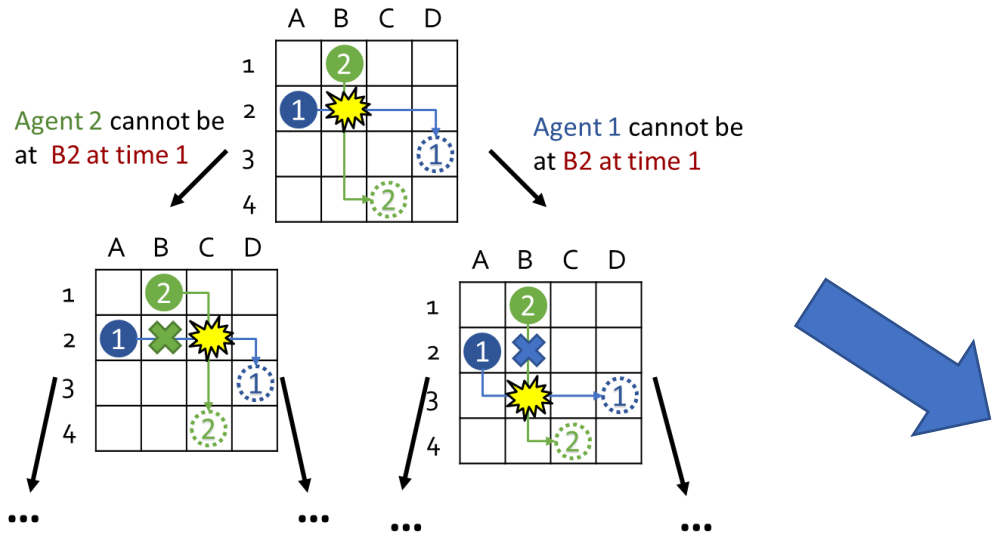
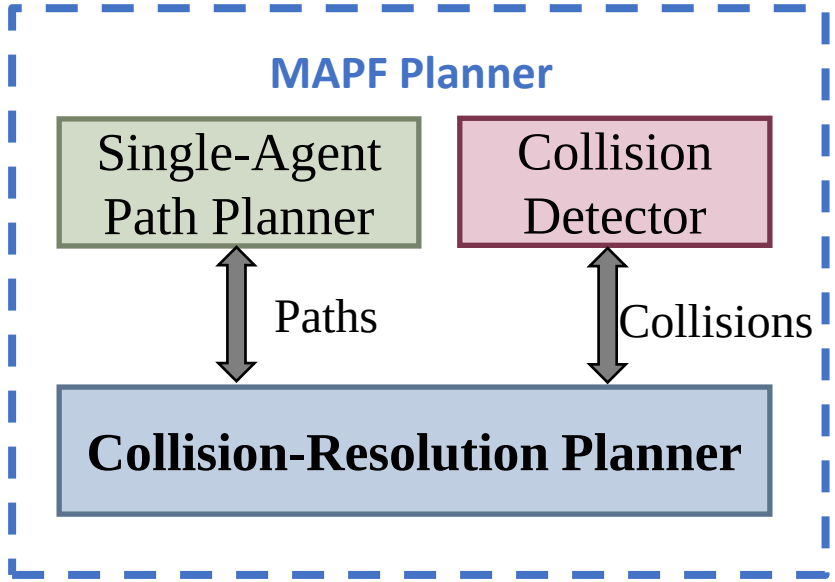
Conflict-Based Search (CBS)





How to resolve collisions?

How to choose nodes?

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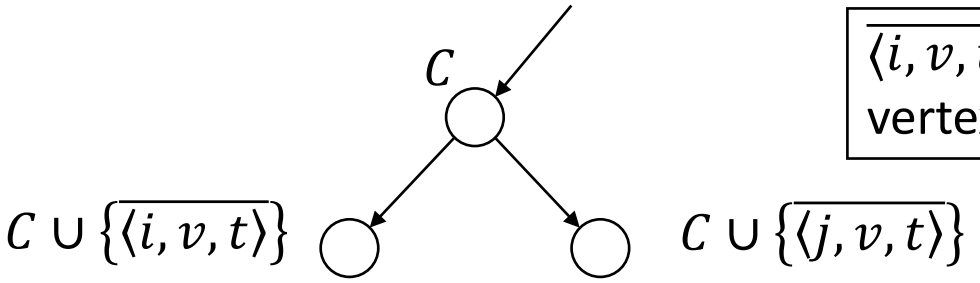
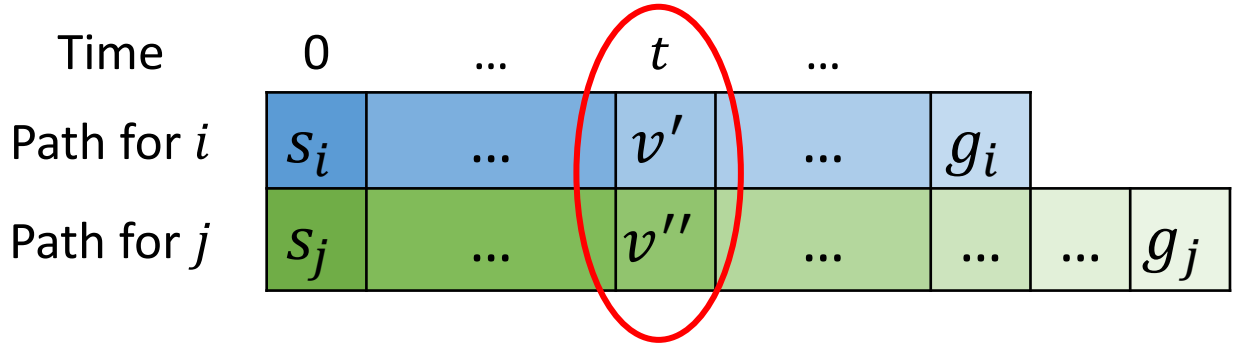
CBS Splitting

- To resolve a collision between agents i and j at vertex v at time t:



$\overline{\langle i, v, t \rangle}$: Agent i cannot be at vertex v at time t.

- The search spaces (i.e., sets of paths that satisfy the constraints) of the two child nodes are **not disjoint**!
  - The following pair of paths satisfies both constraints.



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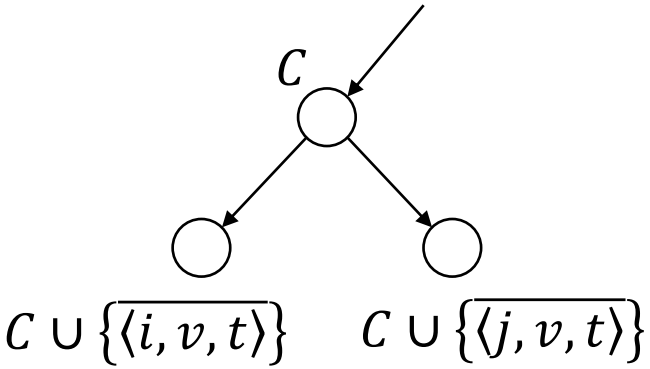
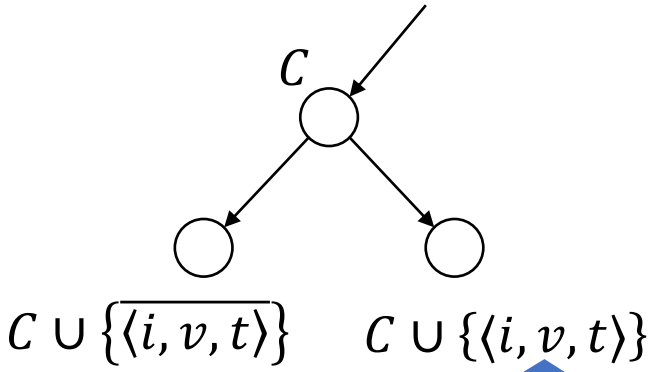
Disjoint Splitting [ICAPS'19]

- Non-disjoint splitting:



- Negative constraint $\overline{\langle i, v, t \rangle}$:
  - Agent i cannot be at v at time t.

- Disjoint splitting [ICAPS'19]:



- **Positive constraint $\langle i, v, t \rangle$**:
  - Agent i must be at v at time t.
  - Any other agents (including agent j) cannot be at v at time t.

J. Li, D. Harabor, P. Stuckey, A. Felner, H. Ma and S. Koenig. Disjoint Splitting for Multi-Agent Path Finding with Conflict-Based Search. **ICAPS**, 2019.

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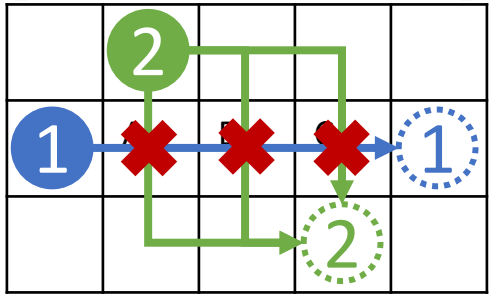
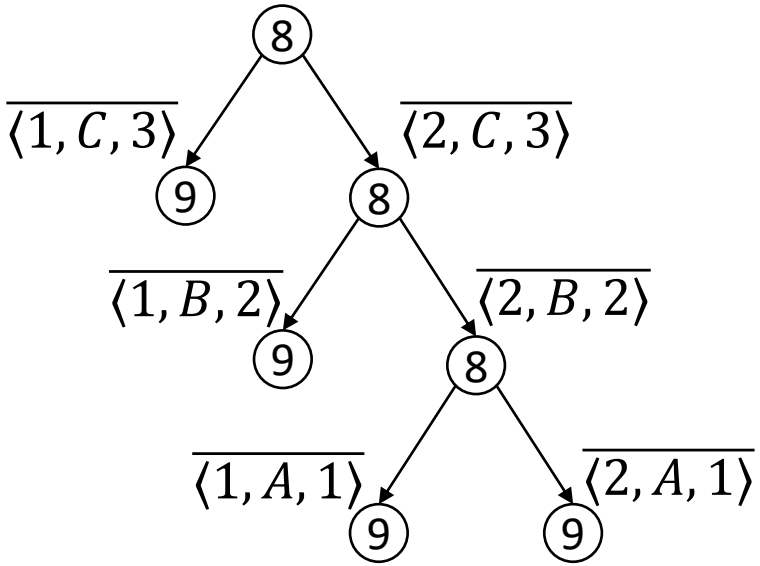
Disjoint Splitting [ICAPS'19]



- Non-disjoint splitting:



J. Li, D. Harabor, P. Stuckey, A. Felner, H. Ma and S. Koenig. Disjoint Splitting for Multi-Agent Path Finding with Conflict-Based Search. **ICAPS**, 2019.

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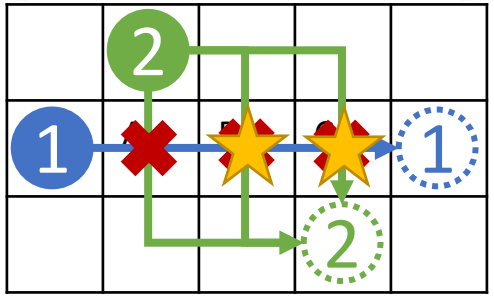
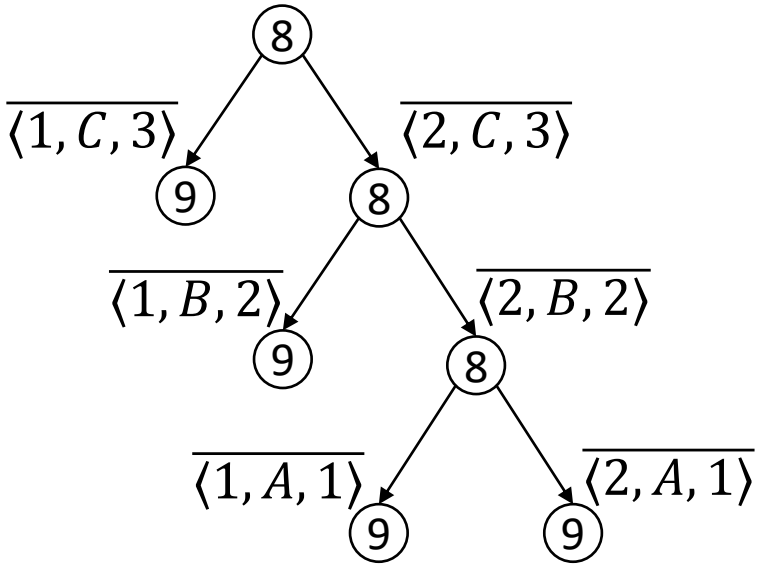
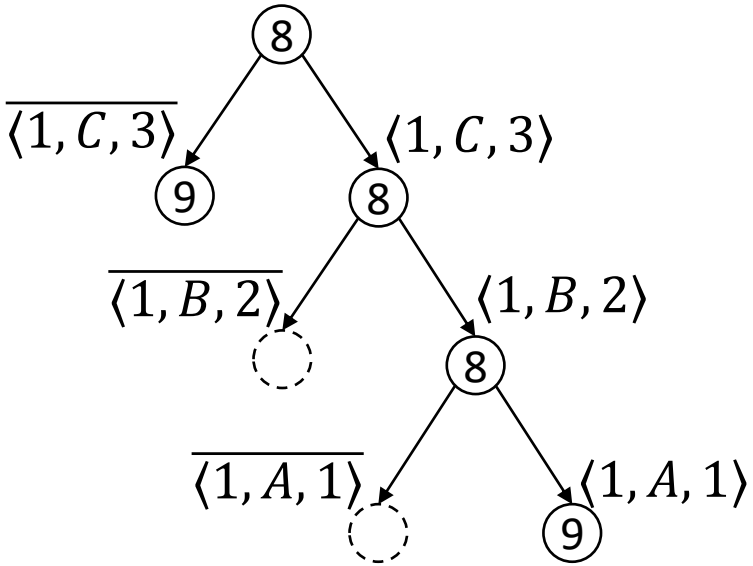
Disjoint Splitting [ICAPS'19]



- Non-disjoint splitting:



- Disjoint splitting:



J. Li, D. Harabor, P. Stuckey, A. Felner, H. Ma and S. Koenig. Disjoint Splitting for Multi-Agent Path Finding with Conflict-Based Search. **ICAPS**, 2019.

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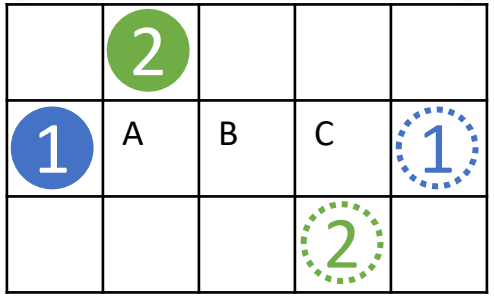
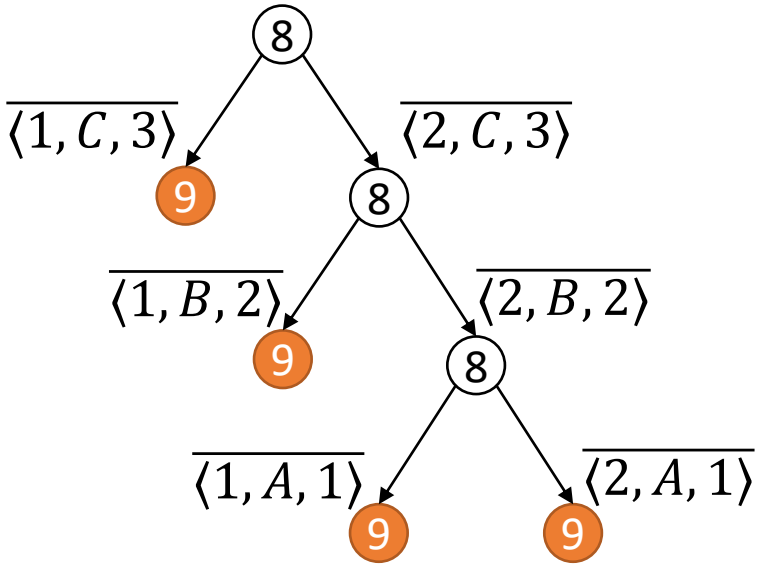
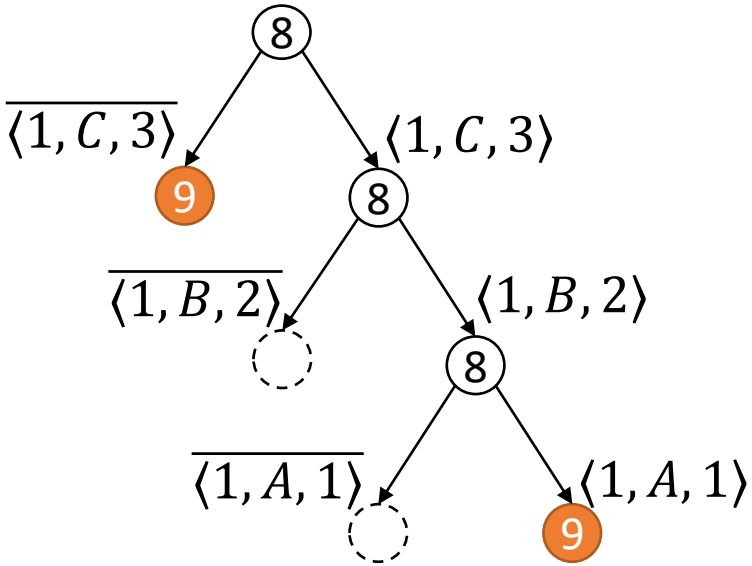
Disjoint Splitting [ICAPS'19]



- Non-disjoint splitting:



- Disjoint splitting:



J. Li, D. Harabor, P. Stuckey, A. Felner, H. Ma and S. Koenig. Disjoint Splitting for Multi-Agent Path Finding with Conflict-Based Search. **ICAPS**, 2019.

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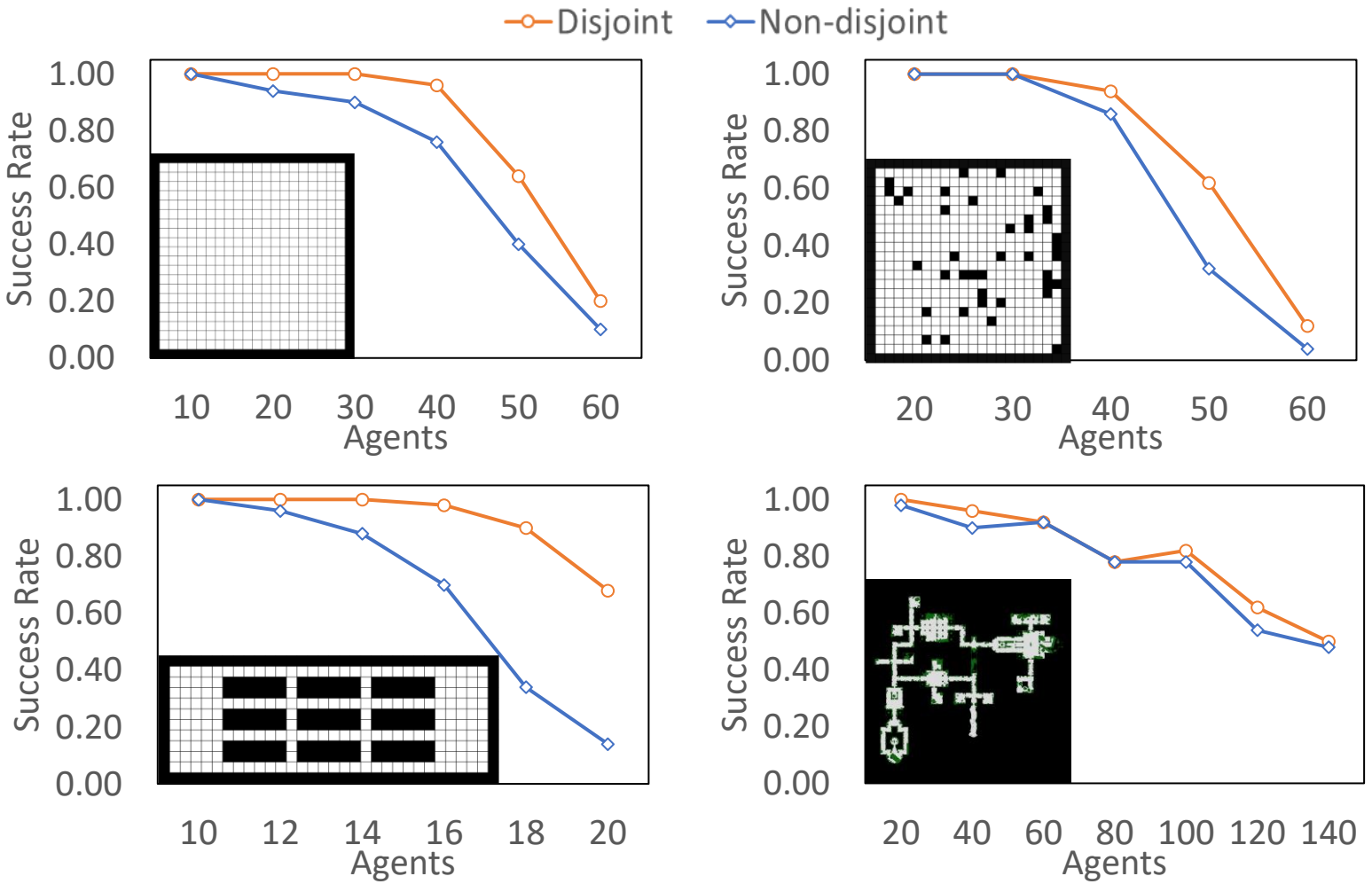
Disjoint Splitting [ICAPS'19]

Success rate (%solved instances within 5 minutes)



J. Li, D. Harabor, P. Stuckey, A. Felner, H. Ma and S. Koenig. Disjoint Splitting for Multi-Agent Path Finding with Conflict-Based Search. **ICAPS**, 2019.

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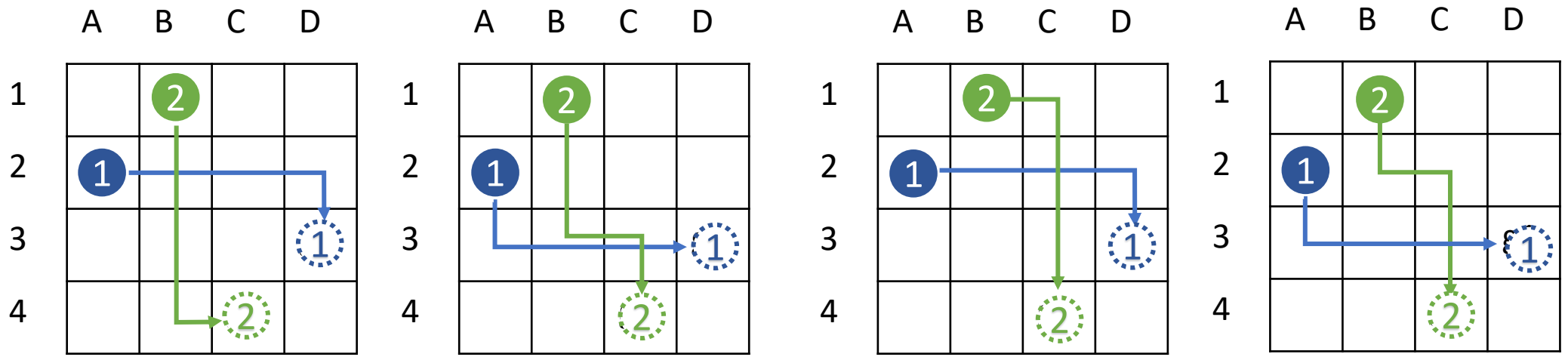
Collision Symmetries [AAAI'19]



J. Li, D. Harabor, P. J. Stuckey, H. Ma and S. Koenig. Symmetry-Breaking Constraints for Grid-Based Multi-Agent Path Finding. **AAAI**, 2019.

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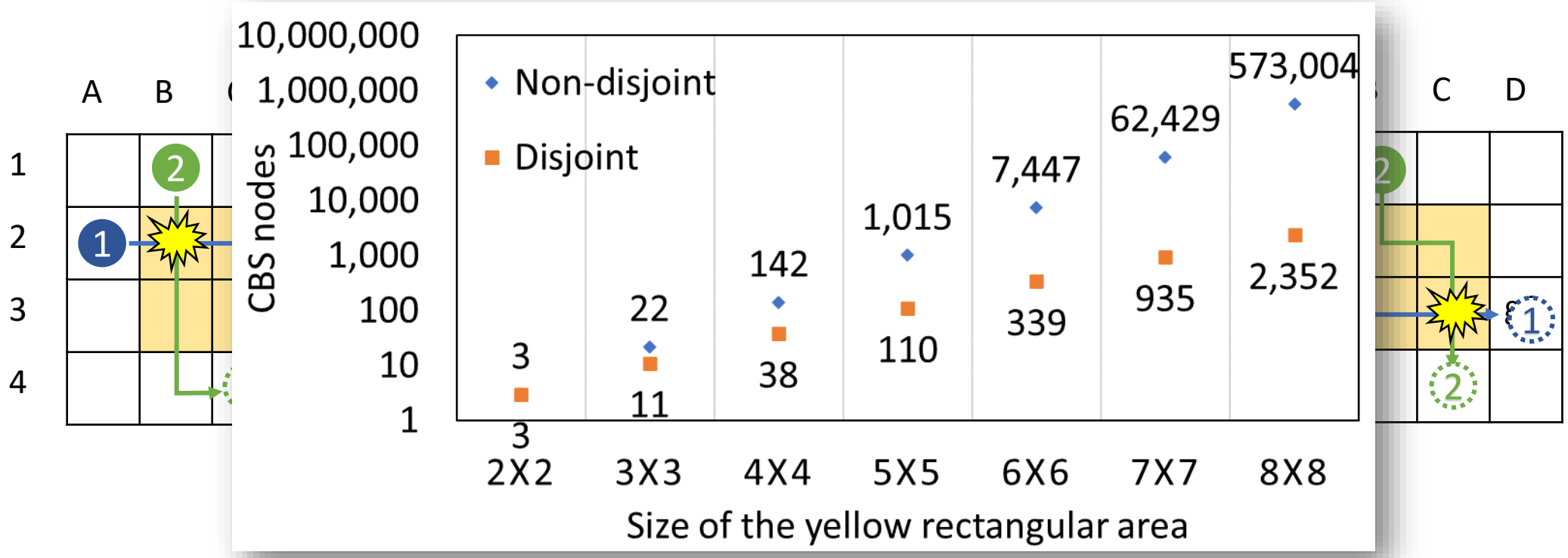
Collision Symmetries [AAAI'19]



J. Li, D. Harabor, P. J. Stuckey, H. Ma and S. Koenig. Symmetry-Breaking Constraints for Grid-Based Multi-Agent Path Finding. **AAAI**, 2019.

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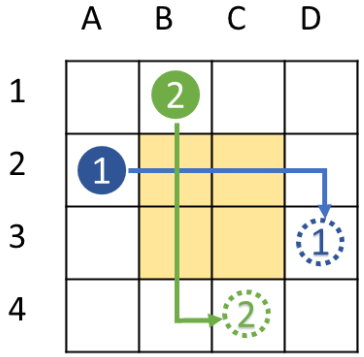
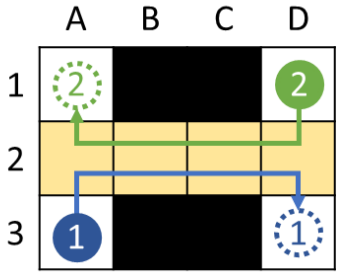
Collision Symmetries [AAAI'19, ICAPS'20, AIJ'21]

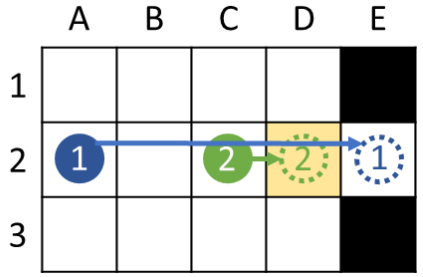
Rectangle symmetry



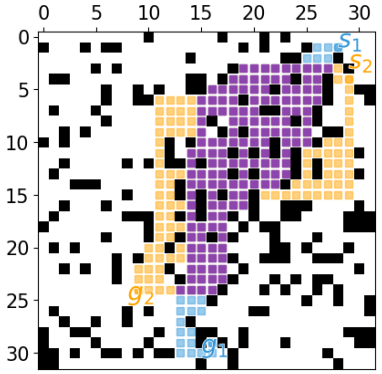
Corridor symmetry



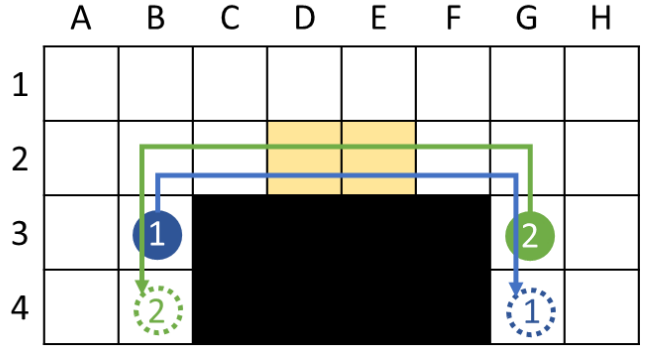
Target symmetry



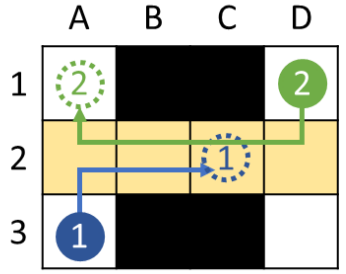
Generalized rectangle symmetry



Pseudo-corridor symmetry



Corridor-target symmetry



J. Li, D. Harabor, P. J. Stuckey, H. Ma and S. Koenig. Symmetry-Breaking Constraints for Grid-Based Multi-Agent Path Finding. **AAAI**, 2019.
J. Li, G. Gange, D. Harabor, P. J. Stuckey, H. Ma and S. Koenig. New Techniques for Pairwise Symmetry Breaking in Multi-Agent Path Finding. **ICAPS**, 2020.
J. Li, D. Harabor, P. J. Stuckey, H. Ma, G. Gange, and S. Koenig. Pairwise symmetry reasoning for multi-agent path finding search. **Artificial Intelligence**, 2021.

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Symmetry-Breaking Constraints [AAAI'19]

- The symmetry-breaking techniques
  - add **a set of constraints** (instead of a single constraint) to each CBS node,
  - resolve the symmetry **in a single branching step**, and
  - preserve the **completeness and optimality** of CBS.

J. Li, D. Harabor, P. J. Stuckey, H. Ma and S. Koenig. Symmetry-Breaking Constraints for Grid-Based Multi-Agent Path Finding. **AAAI**, 2019.

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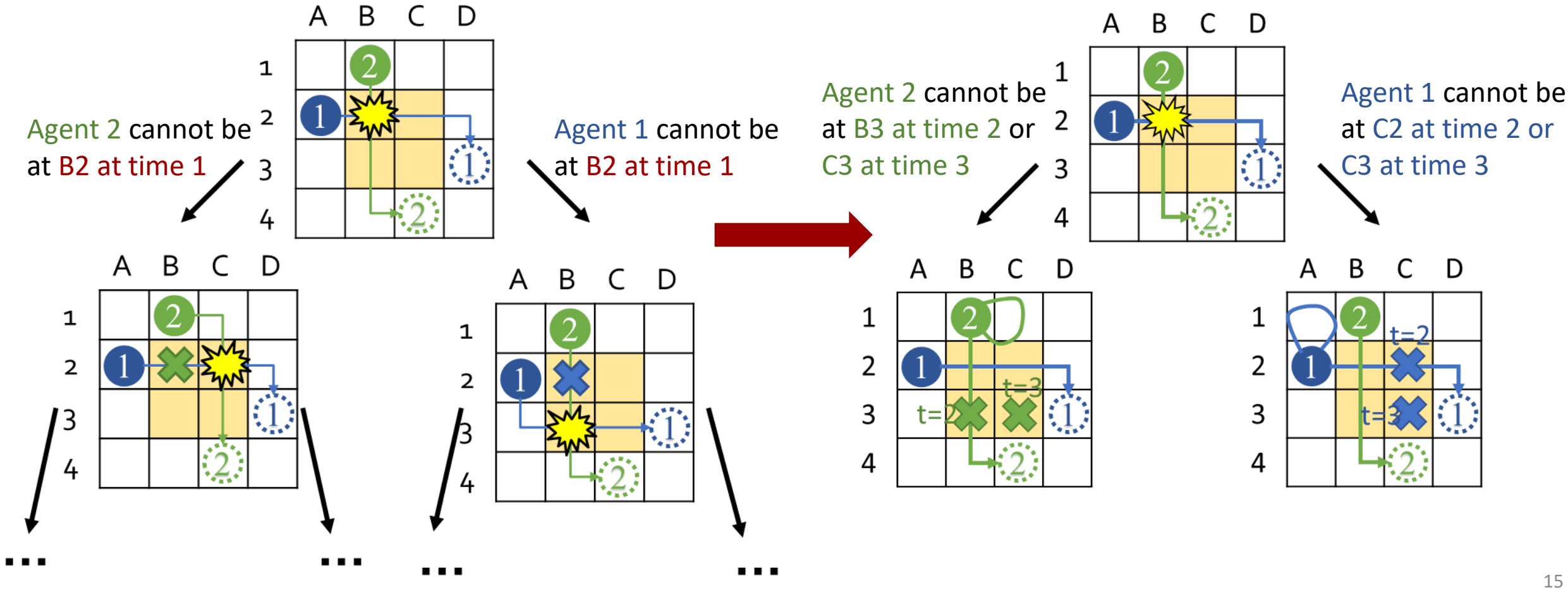
Symmetry-Breaking Constraints [AAAI'19]



J. Li, D. Harabor, P. J. Stuckey, H. Ma and S. Koenig. Symmetry-Breaking Constraints for Grid-Based Multi-Agent Path Finding. **AAAI**, 2019.

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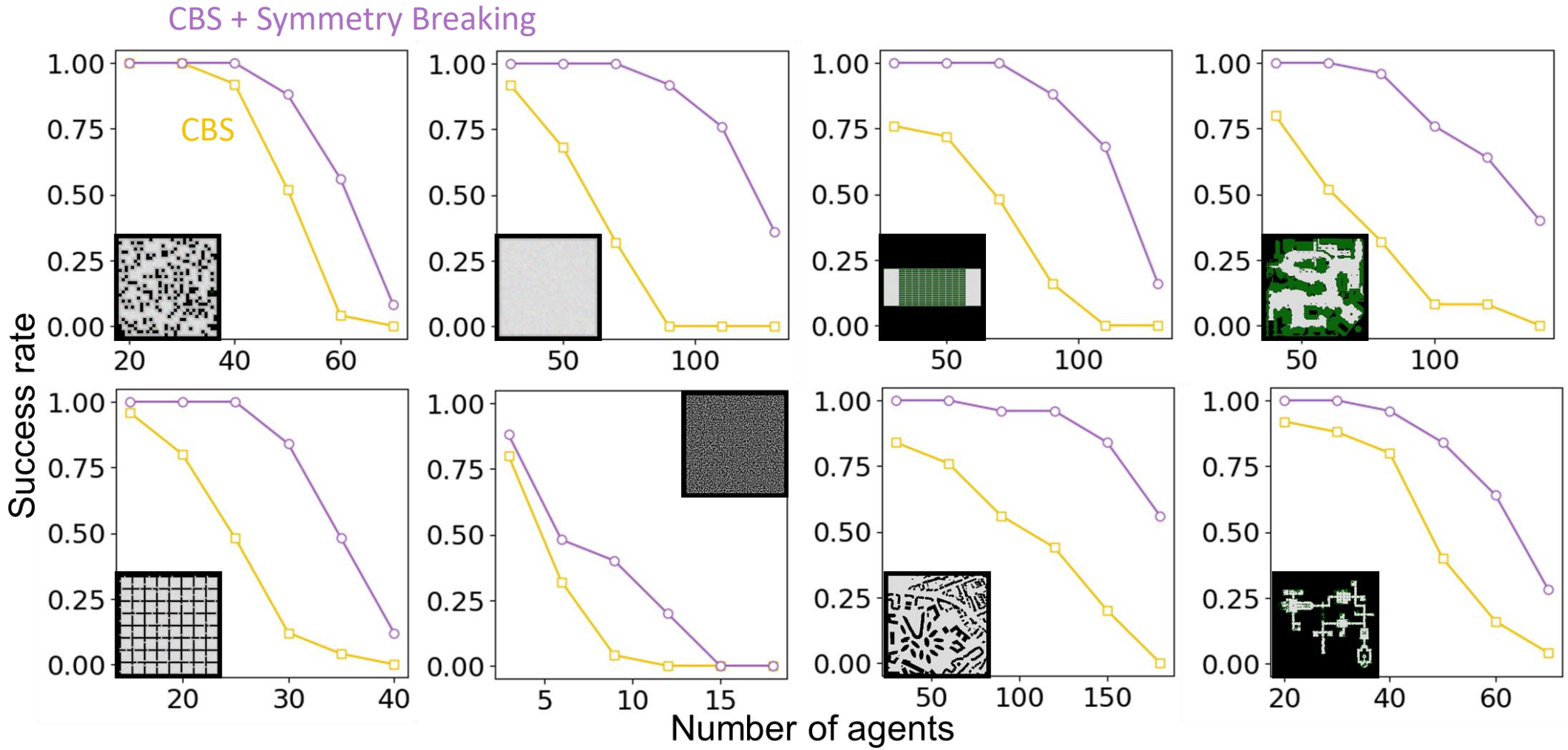
Experiments



Runtime limit: 1 minute

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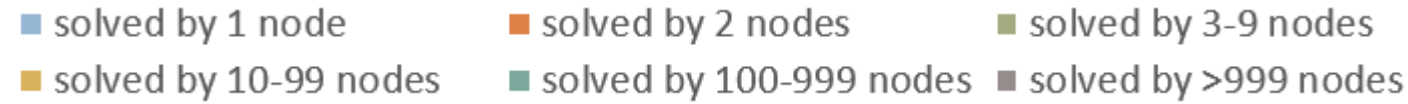
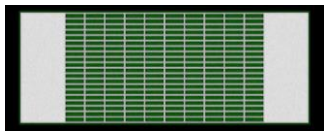
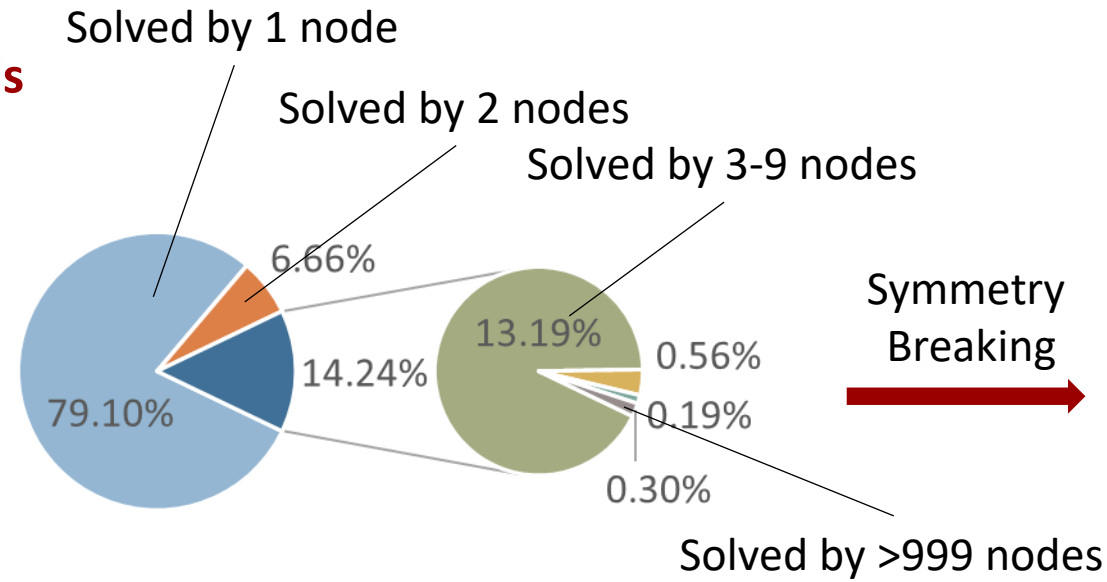
Experiments



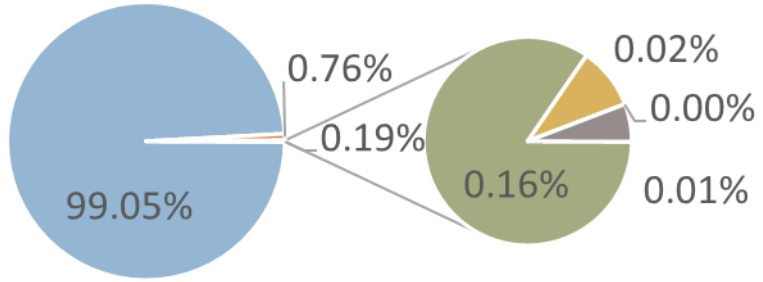
2 agent analysis

Warehouse map

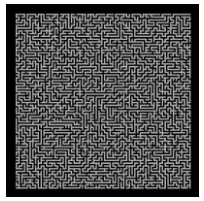


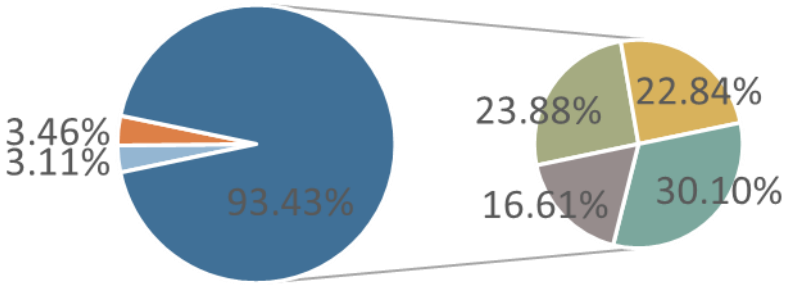


Symmetry Breaking

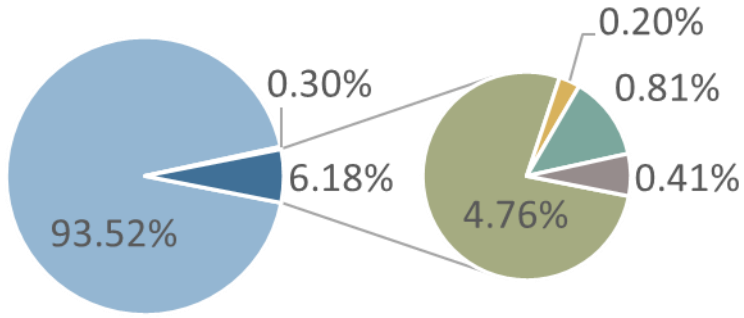


Maze map





Symmetry Breaking



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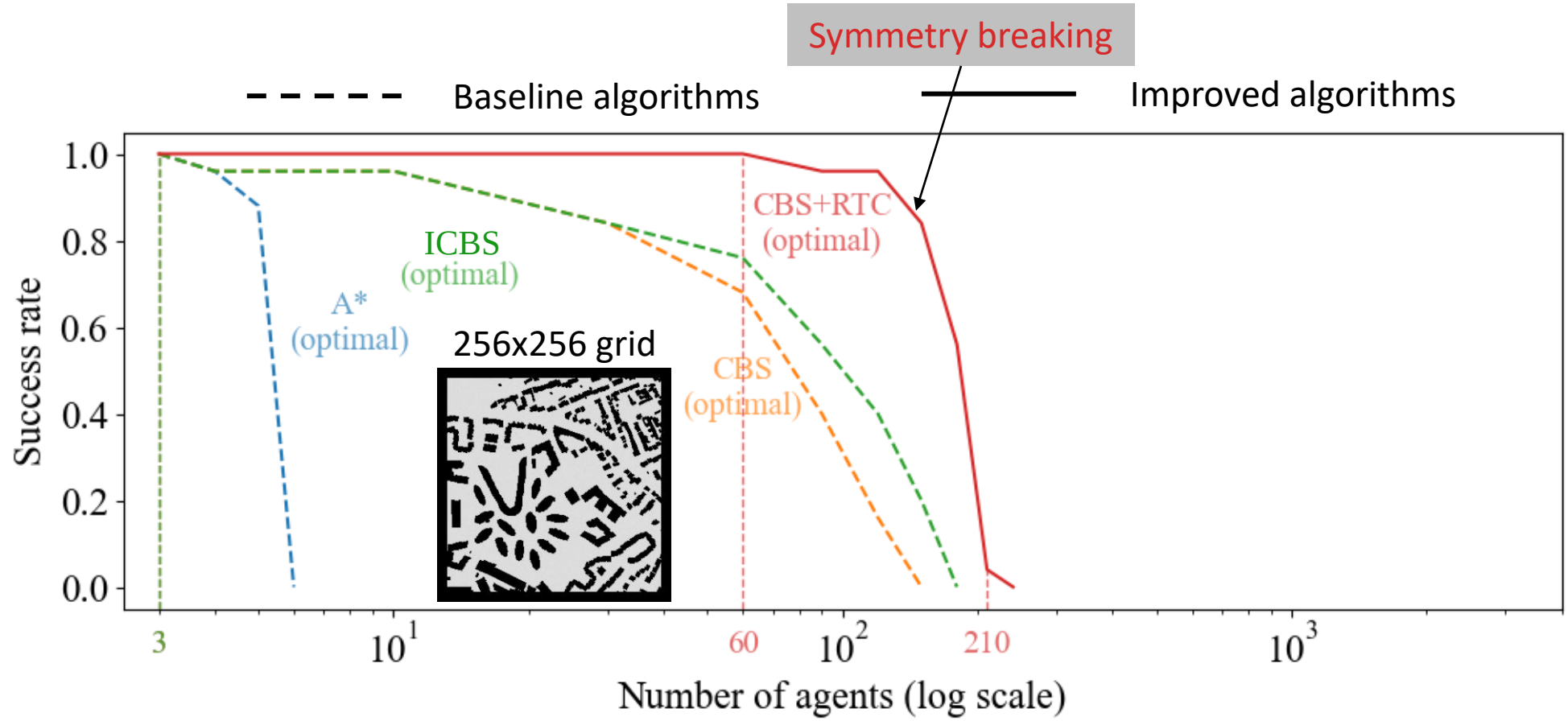
Adding Symmetry Reasoning



Runtime limit: 1 minute

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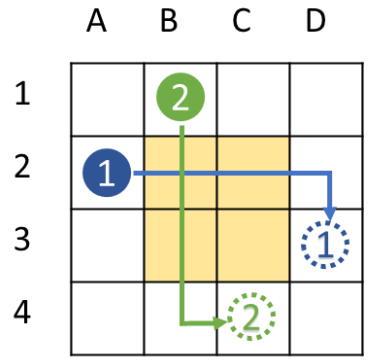
Symmetry Reasoning for Other Solvers

- Such symmetries are later discovered in other state-of-the-art MAPF solvers, and our symmetry reasoning techniques are shown to be effective as well:
  - Integer linear programming solver BCP [Lam et al 2019, 2020],
  - Constraint programming solver Lazy CBS [Lam and L. Bodic 2020],
  - SAT-based solver SAT-MDD [Surynek et al 2020].



E. Lam, P. L. Bodic, D. Harabor and P. J. Stuckey. Branch-and-cut and-price for multi-agent pathfinding. **IJCAI**, 2019.
E. Lam and P. L. Bodic. New valid inequalities in branch-and-cut-and-price for multi-agent path finding. **ICAPS**, 2020.
P. Surynek, **J. Li**, H. Zhang, T. K. S. Kumar and S. Koenig. Mutex propagation for SAT-based multi-agent path finding. **PRIMA**, 2020.

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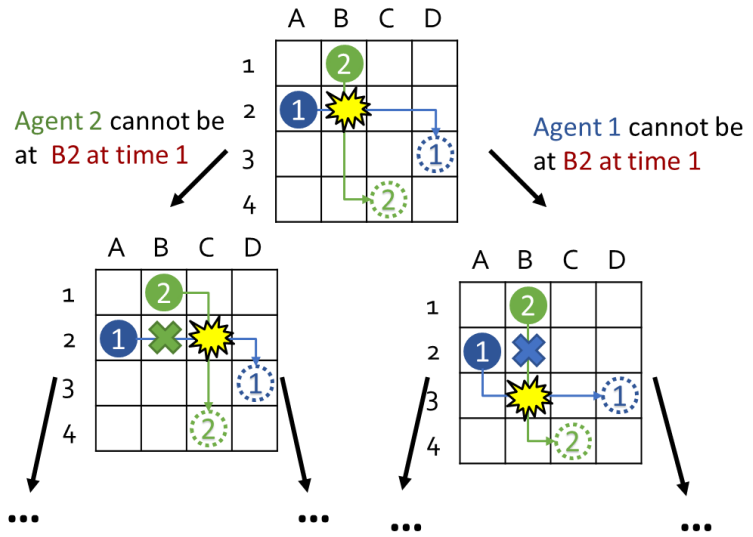
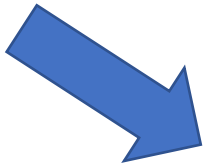
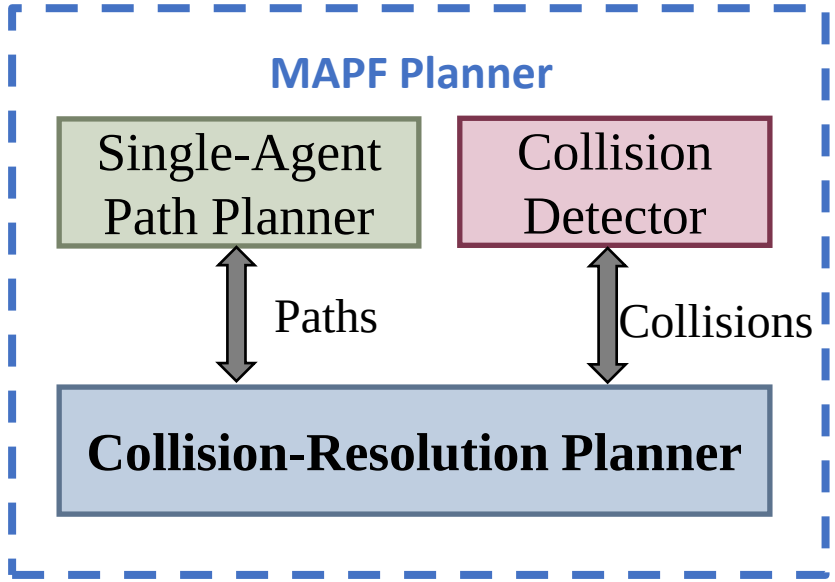
Conflict-Based Search (CBS)







How to resolve collisions?

How to choose nodes?

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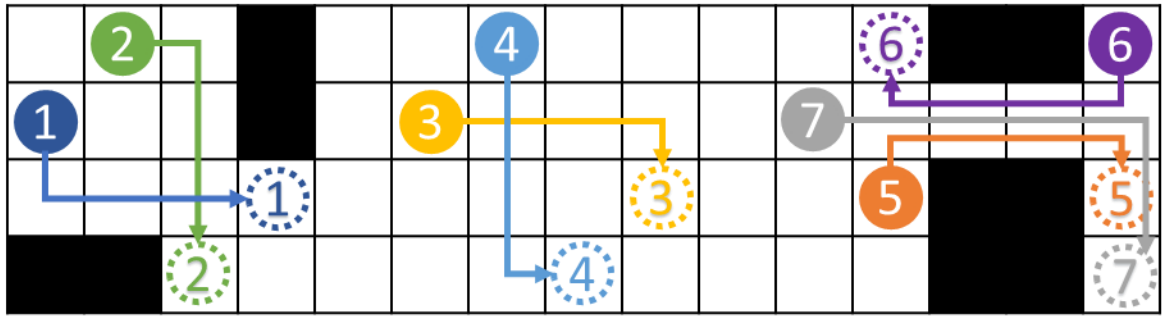
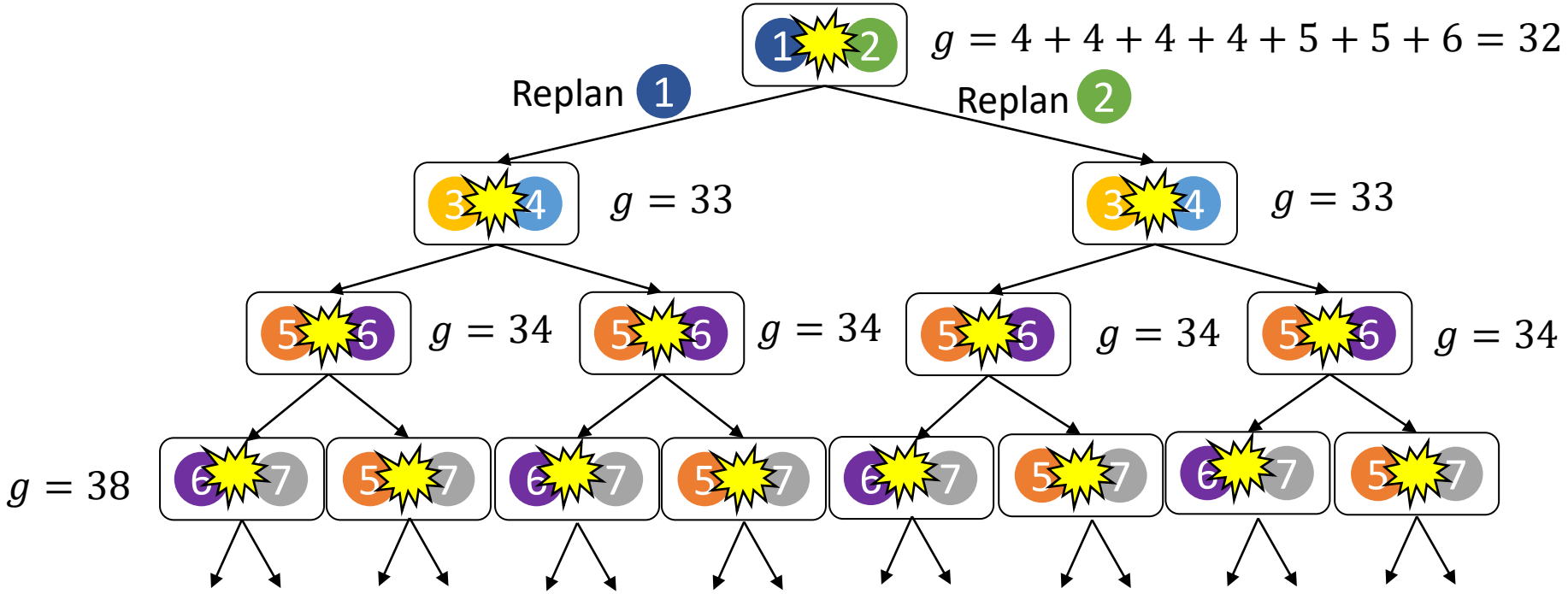
When We Have >2 Agents





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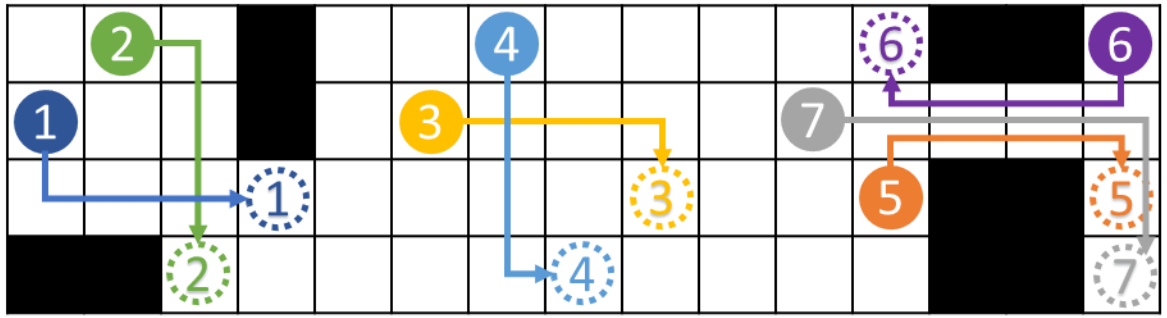
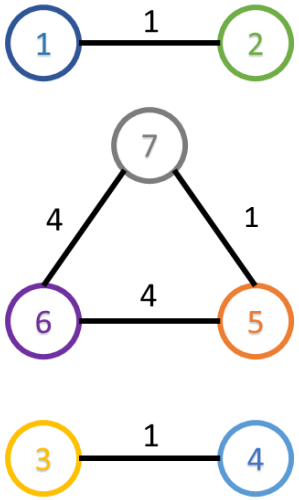
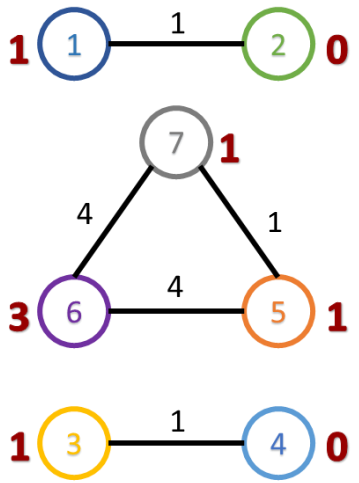
Adding Admissible Heuristics [IJCAI'19]



- Edge-weighted dependency graph
- Edge-weighted minimum vertex cover





$$h = 1 + 0 + 1 + 0 + 3 + 1 + 1 = 7$$

J. Li, E. Boyarski, A. Felner, H. Ma and S. Koenig. Improved Heuristics for Conflict-Based Search for Multi-Agent Path Finding. **IJCAI**, 2019.

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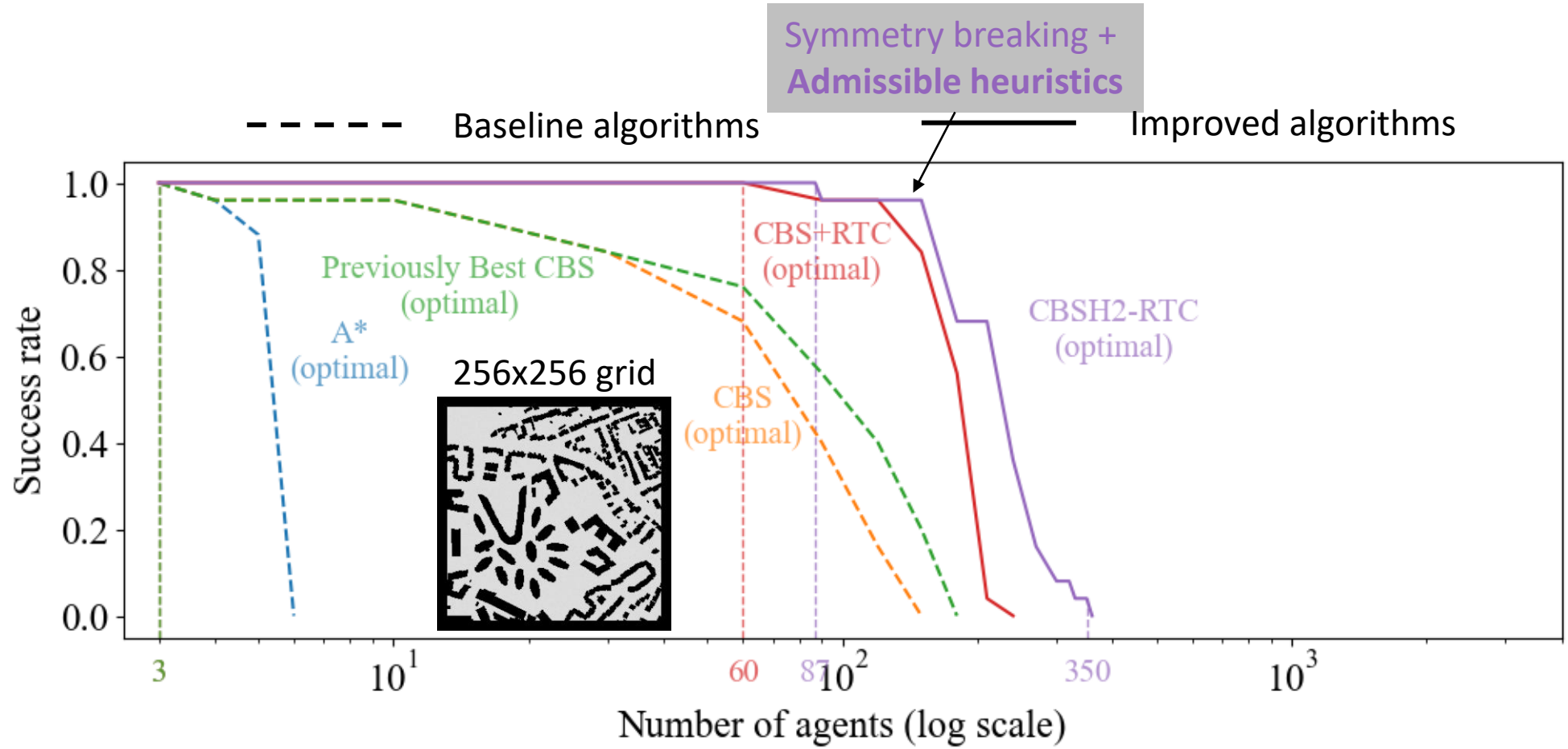
Adding Admissible Heuristics [IJCAI'19]



Runtime limit: 1 minute

J. Li, E. Boyarski, A. Felner, H. Ma and S. Koenig. Improved Heuristics for Conflict-Based Search for Multi-Agent Path Finding. **IJCAI**, 2019.

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Admissible Heuristics Can Be Further Improved

- We are the first to introduce admissible heuristics to CBS, and such heuristics can be further improved by
  - Solving the edge-weighted minimum vertex cover incrementally [Boyarski et al 2020],
  - Computing a tighter cost estimate from the dependency graph [Boyarski et al 2021],
  - Combining with Lagrangian Relax-and-Cut scheme [Mogali et al 2020].

E. Boyarski, A. Felner, D. Harabor, P. Stuckey, L. Cohen, **J. Li** and S. Koenig. Iterative-deepening conflict-based search. **IJCAI**, 2020.
E. Boyarski, A. Felner, P. Le Bodic, D. Harabor, P. Stuckey and S. Koenig. f-aware conflict prioritization & improved heuristics for conflict-based search. **AAAI**, 2021.
J. Mogali, W.-J. Hoeve and S. Smith. Template matching and decision diagrams for multi-agent path finding. **CPAIOR**, 2020.

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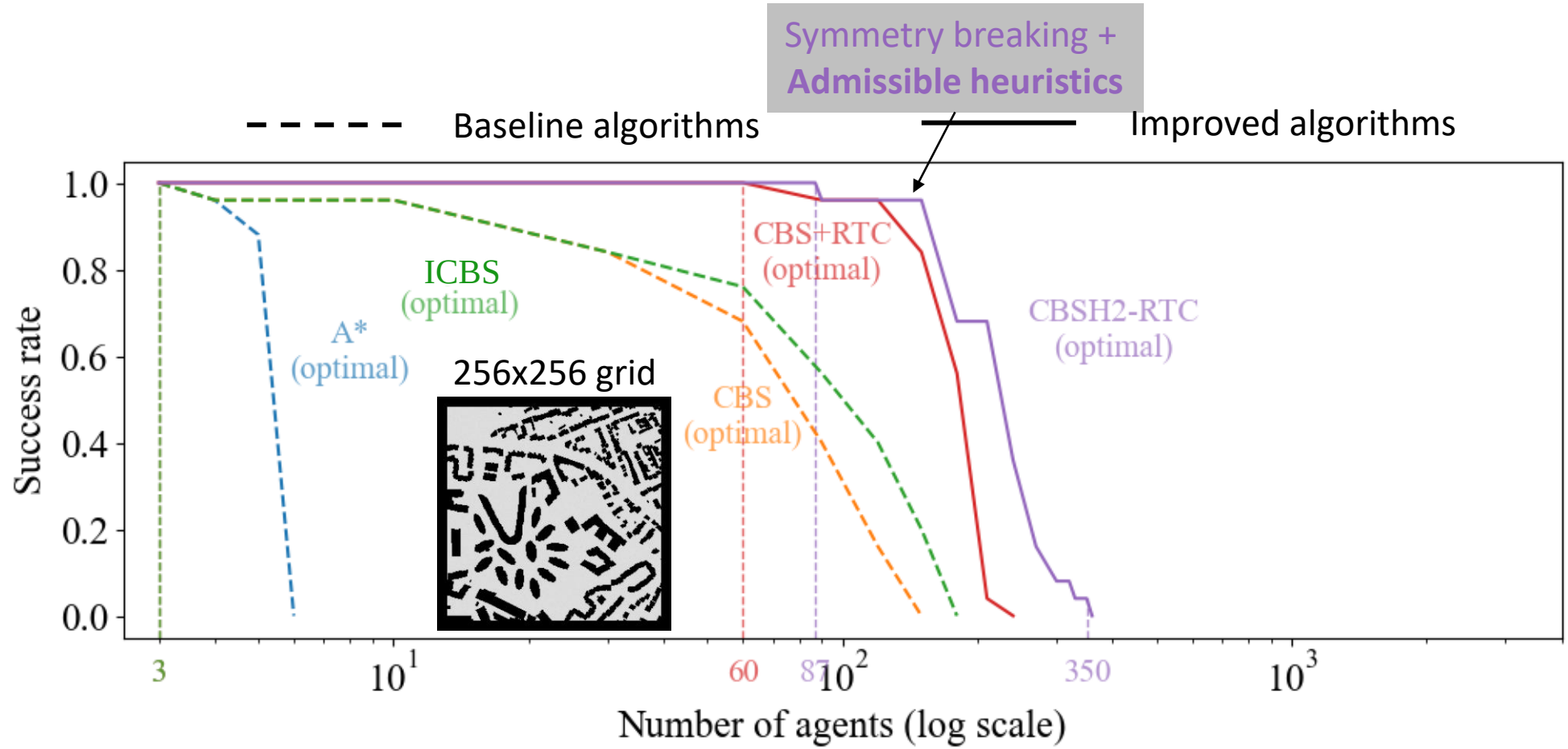
Adding Admissible Heuristics [IJCAI'19]



Runtime limit: 1 minute

J. Li, E. Boyarski, A. Felner, H. Ma and S. Koenig. Improved Heuristics for Conflict-Based Search for Multi-Agent Path Finding. **IJCAI**, 2019.

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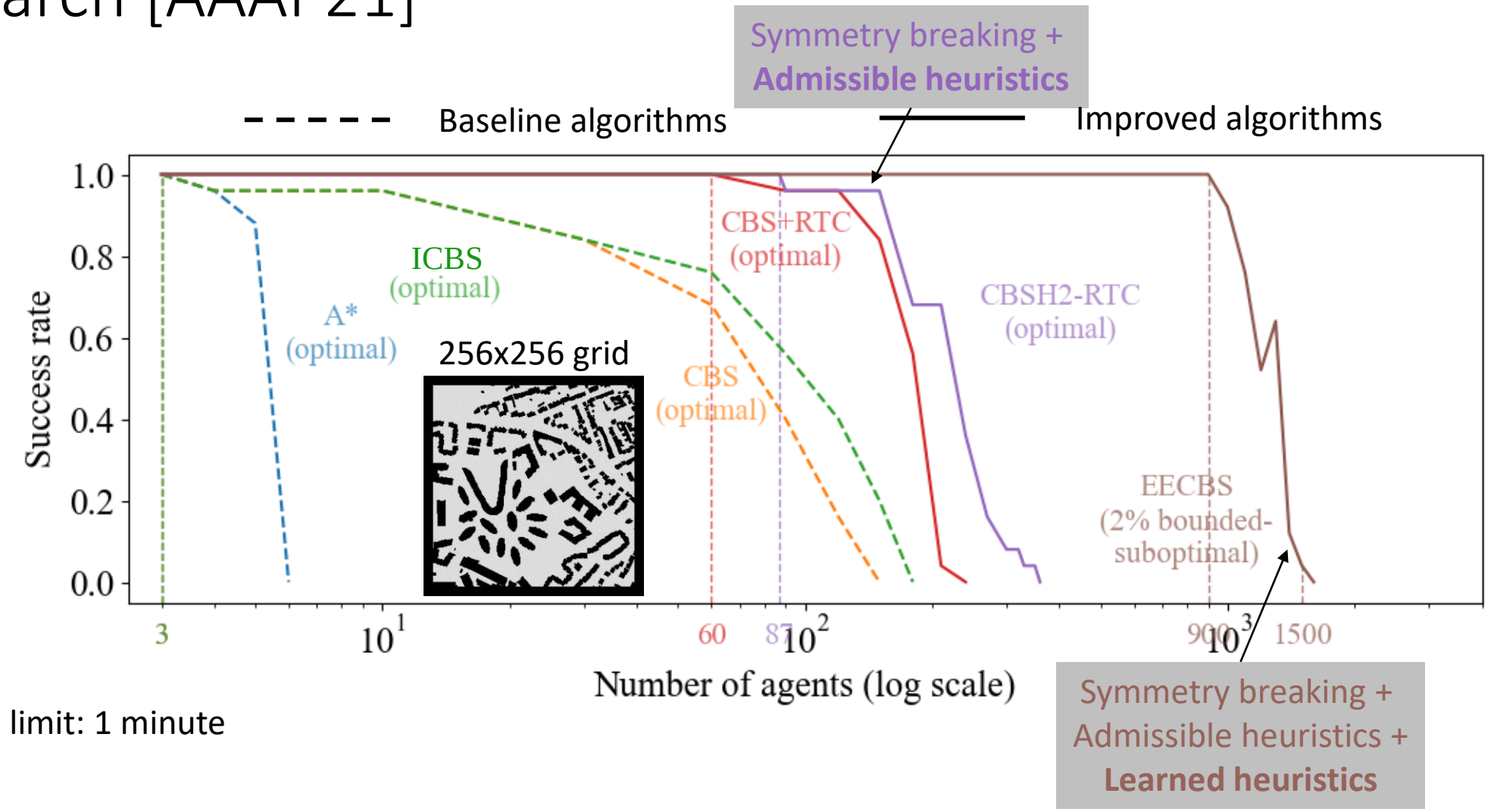
Adding Learned Heuristics with Bounded-Suboptimal Search [AAAI'21]



Runtime limit: 1 minute

J. Li, W. Ruml and S. Koenig. EECBS: Bounded-Suboptimal Search for Multi-Agent Path Finding. **AAAI**, 2021.

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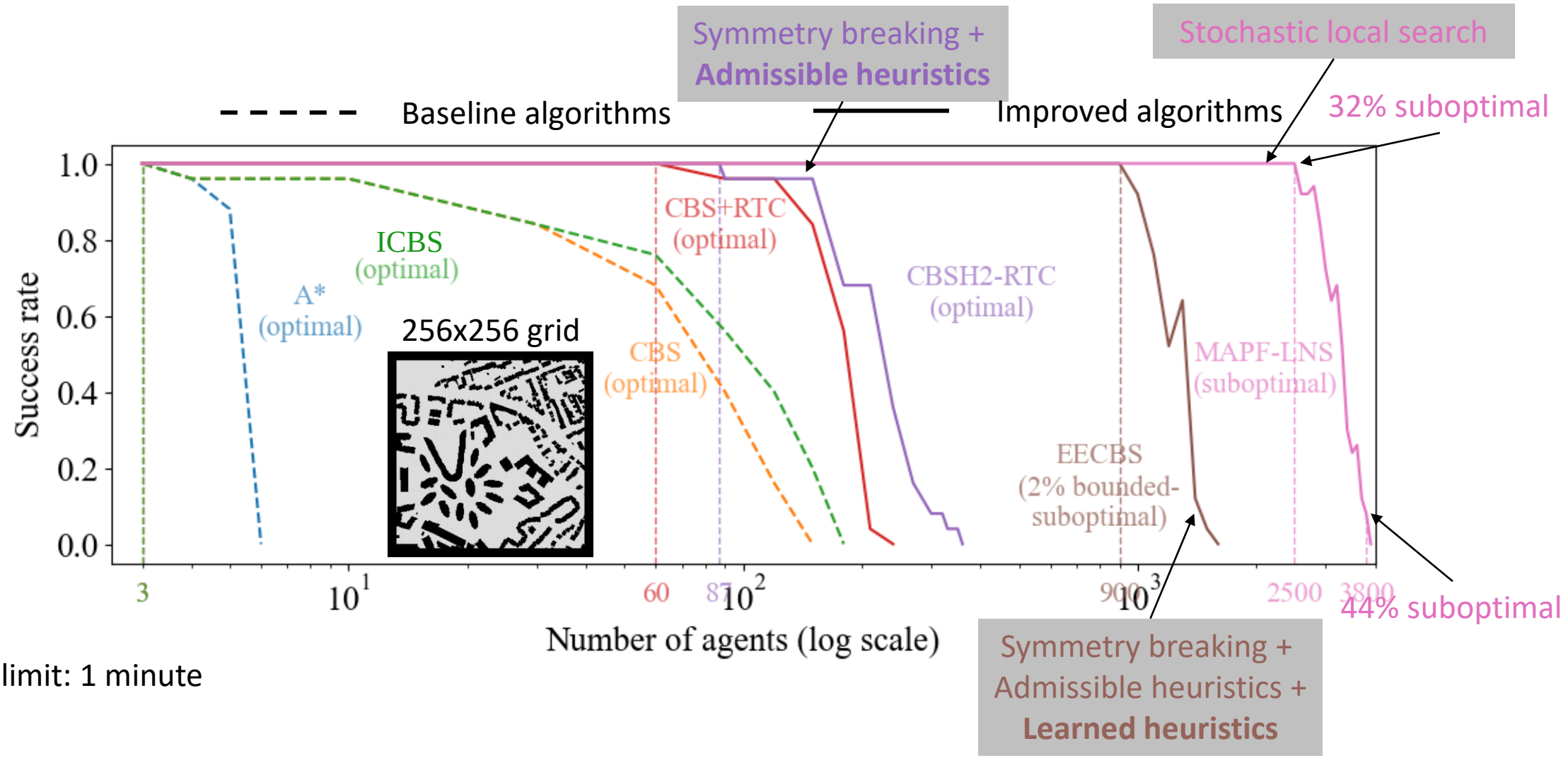
Stochastic Local Search [AAAI'22]



Runtime limit: 1 minute

J. Li, Z. Chen, D. Harabor, P. J. Stuckey and S. Koenig. RMAPF: Repairing Multi-Agent Path Finding via Large Neighborhood Search. **AAAI**, 2022.