On Bidirectional Heuristic Search in Classical Planning: An Analysis of BAE*

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Motivation

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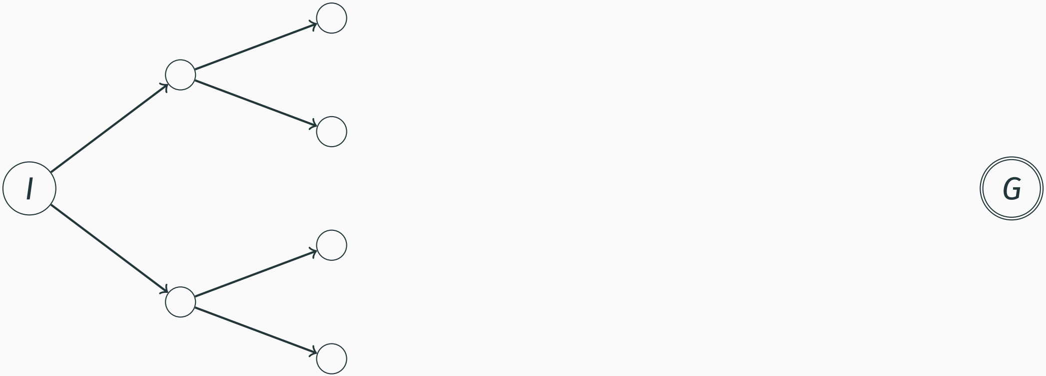

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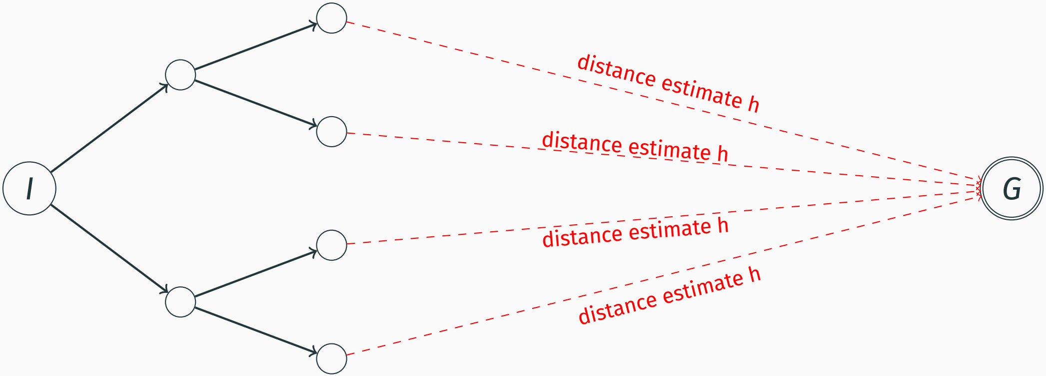

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distance estimate h
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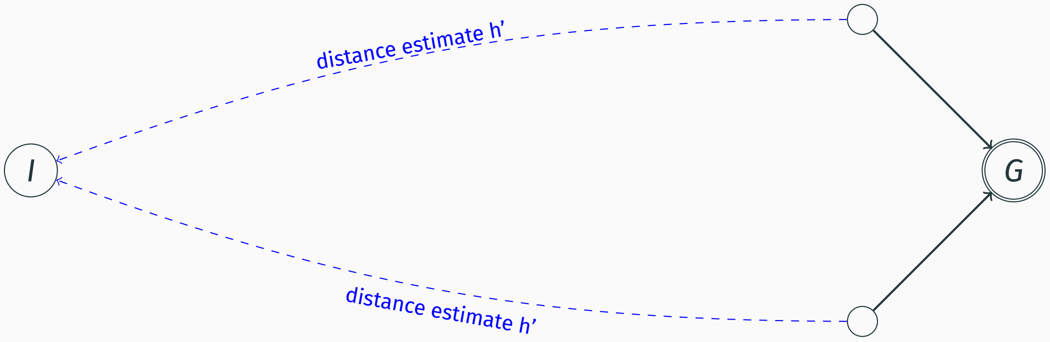

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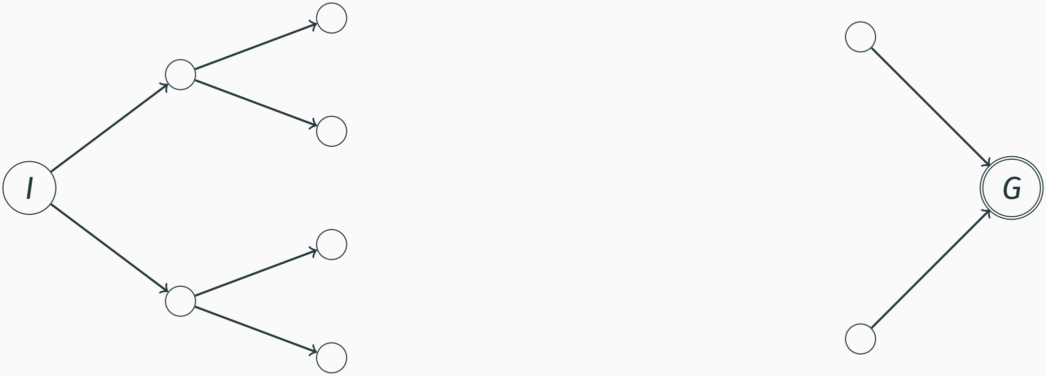

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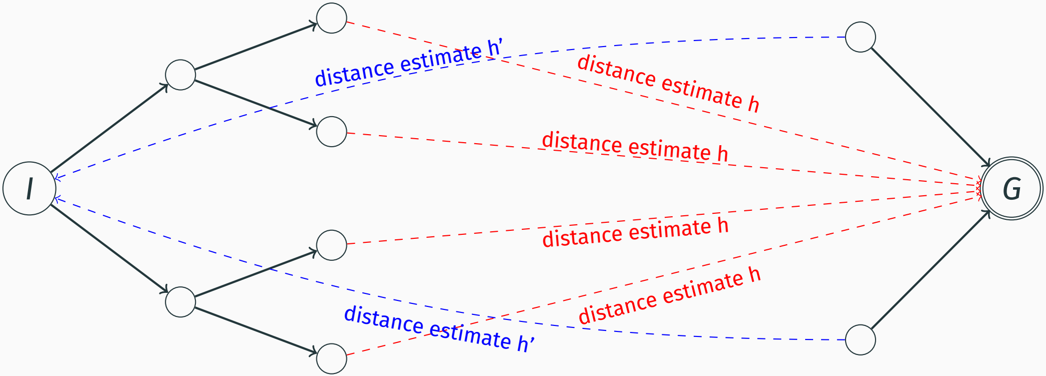

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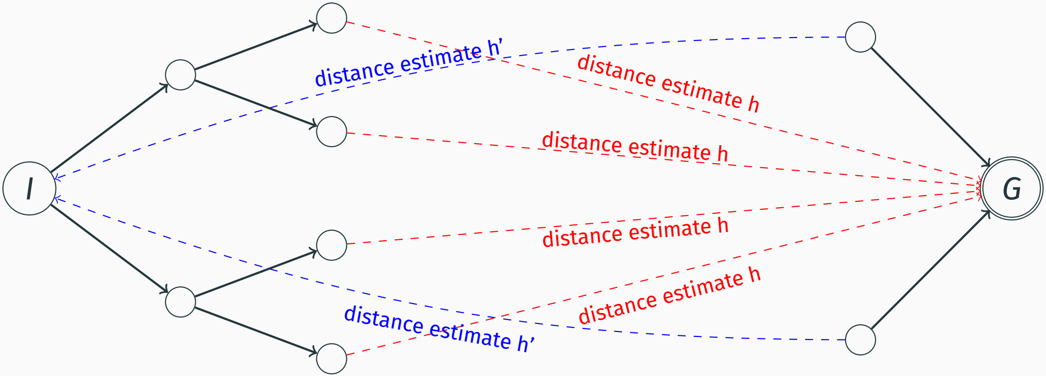

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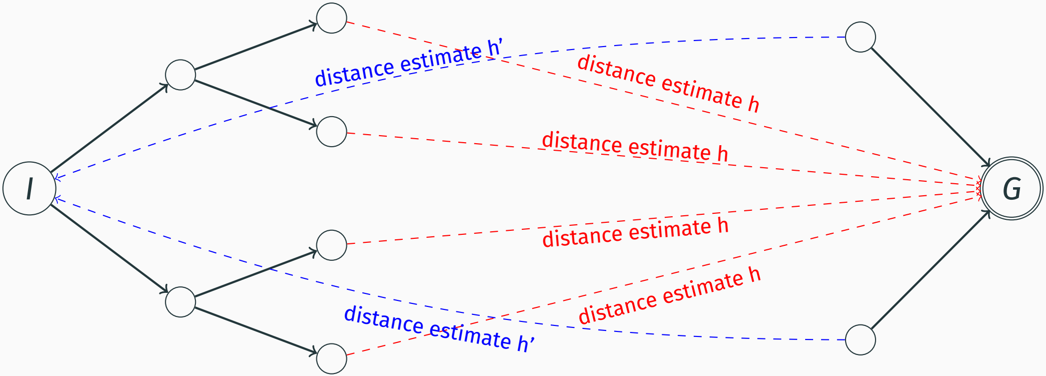

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⇝ Can we transfer these works to classical planning?

Heuristic Search

- Most prominent algorithm: A* (backward A^*_b)
  - Explores the state space unidirectionally
- Bidirectional heuristic search performs two searches simultaneously
  - Can outperform unidirectional search
  - Generally considered inefficient [BK15]

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Rekindled interest in bidirectional heuristic search

- Improved theoretical understanding [ECS+17]
- Development of new successful algorithms
  - NBS [ECS+17]
  - BAE* [Sad13, ARB20]

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  - NBS [ECS+17]
  - BAE* [Sad13, ARB20]
    - ⇝ Excellent performance (compared to more complex algorithms)
    - ⇝ Promising candidate for planning

BAE* in a Nutshell

- Bidirectional A* with Error [Sad13, ARB20]
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- $h_F(n) = 4$
- $f_F(n) = 7$

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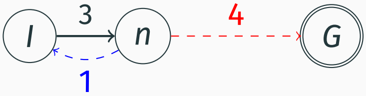

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- $f_F(n) = 7$
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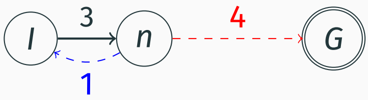

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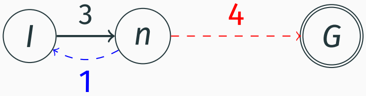

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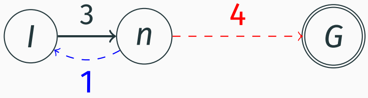
  - Diff-value: $d_x(n) = g_x(n) - h_{\overline{x}}(n)$
- Termination: lower bound $\geq$ upper bound
  - Lower: $\frac{bMin_f + bMin_b}{2}$
  - Upper: cost of best solution found so far



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Bidirectional Search in Planning

Algorithms like BAE* come with some challenges

- Forward search is easy
- Backward search is tricky
  - Multiple goal states (sometimes exponentially many)
  - Regressing a state with an action $\rightsquigarrow$ multiple predecessors

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- Generation of a reversed task [Sud13, GB13, ABFF13]
- Reversed SAS+ tasks often use partial states
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⇝ Here: Reversed task with an explicit state representation

Reversed Task Generation

Initial states

- Goal states of the actual task
- Add initial states directly to open list
  - Alternative: single dummy initial state
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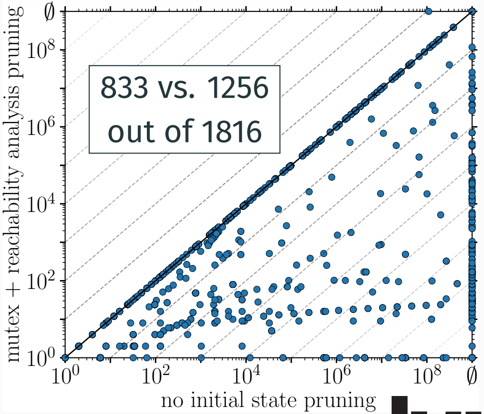

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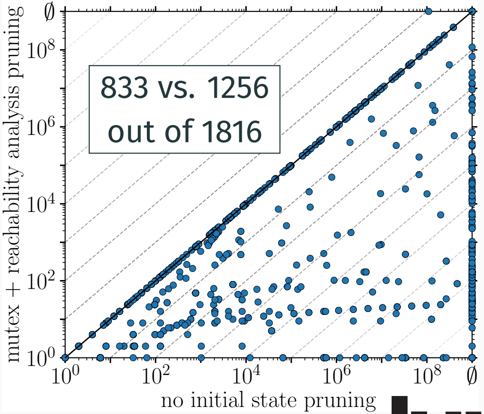

Reversed Operators

- Multiple reversed actions for an action
- In practice often unproblematic
  - 1.44 reversed actions per action

Empirical Evaluation

- Implemented A_b^* and BAE* in Fast Downward [Hel06]
  - Backward search based on the reversed task
- 3 different consistent heuristics
  - Max heuristic $h^{\max}$ [BG01]
  - Incremental pattern database heuristic h^{iPDB} [HBH+07]
  - Diverse potentials heuristic h^{pot} [SPH15]
- Planning tasks from optimal track of IPCs
- 30 min and 4 GB memory for each task

Coverage

	h^{max}			h^{iPDB}			h^{pot}		
	A*	A^*_b	BAE*	A*	A^*_b	BAE*	A*	A^*_b	BAE*
Sum (1816)	**847**	558	706	**1009**	732	805	**989**	732	841

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Coverage

	h^{max}			h^{iPDB}			h^{pot}		
	A*	A_b^*	BAE*	A*	A_b^*	BAE*	A*	A_b^*	BAE*
blocks (35)	21	22	**30**	28	**32**	31	28	28	**30**
ged (20)	15	15	**20**	19	13	**20**	19	13	**20**
termes (20)	10	8	**15**	13	12	**16**	12	11	**16**
	...			...			...		
Sum (1816)	**847**	558	706	**1009**	732	805	**989**	732	841

Coverage – Possible to Generate Reversed Task

	$h^{\max}$			h^{iPDB}			h^{pot}		
	A*	A^*_b	BAE*	A*	A^*_b	BAE*	A*	A^*_b	BAE*
Sum (1256)	**719**	558	706	**853**	732	805	**848**	732	841

Coverage – Possible to Generate Reversed Task

	$h^{\max}$			h^{iPDB}			h^{pot}		
	A*	A^*_b	BAE*	A*	A^*_b	BAE*	A*	A^*_b	BAE*
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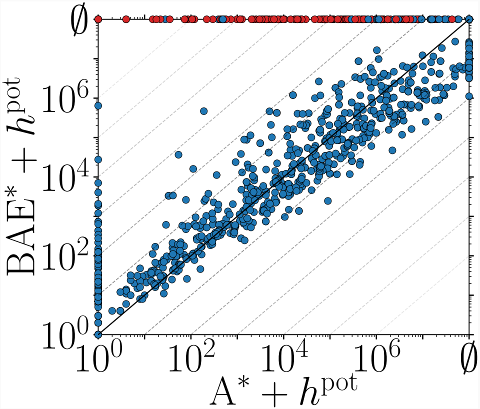
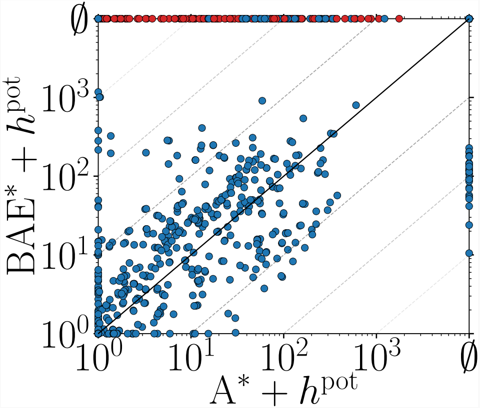
How do these algorithms perform in detail?

BAE* vs. A*

Node Expansions

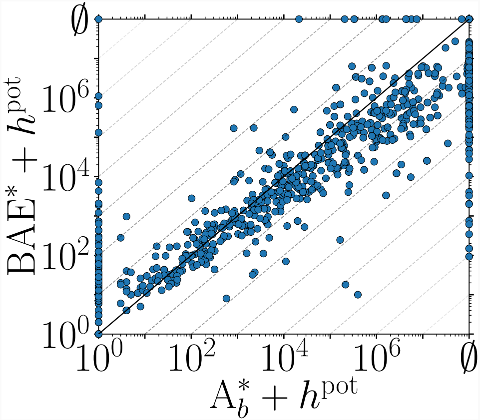


Runtime (seconds)



BAE* vs. Backward A*

Node Expansions



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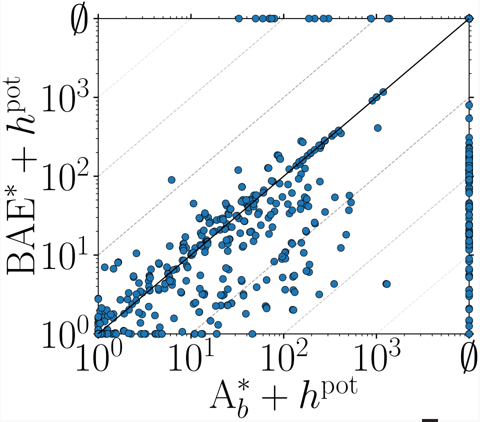

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Complementary Strengths

	Single			Oracle		
	A^*	A^*_b	BAE^*	$\{A^*, A^*_b\}$	$\{A^*, BAE^*\}$	$\{A^*, A^*_b, BAE^*\}$
$h^{\max}$	847	558	706	848	**878**	**878**
h^{iPDB}	1009	732	805	1026	1022	**1031**
h^{pot}	989	732	841	1007	1019	**1030**

Complementary Strengths

	Single			Oracle			Simple Classifier $\mathcal{C}$
	A*	A^*_b	BAE*	{A*, A^*_b}	{A*, BAE*}	{A*, A^*_b, BAE*}	{A*, BAE*}
h^{max}	847	558	706	848	878	878	**856**
h^{iPDB}	**1009**	732	805	1026	1022	1031	986
h^{pot}	989	732	841	1007	1019	1030	**995**

$\mathcal{C}$: Use BAE* if the reversed task satisfies

- #initial states $\leq$ 100 and
- generation time $\leq$ 1sec

$\rightsquigarrow$ 20% of instances

Conclusion

- Analysis of bidirectional heuristic search for classical planning
    - In particular BAE*
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Future Work

- More compact representations of a reversed task
    - Allow partial states in the backward search
- Other bidirectional heuristic search algorithms

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