16-350
Planning Techniques for Robotics

Interleaving Planning and Execution: Incremental Heuristic Search

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Planning during Execution

- Planning is a repeated process!
  - partially-known environments
  - dynamic environments
  - imperfect execution of plans
  - imprecise localization

- Need to be able to re-plan fast!

- Several methodologies to achieve this:
  - anytime heuristic search: return the best plan possible within T msecs
  - incremental heuristic search: speed up search by reusing previous efforts
  - real-time heuristic search: plan few steps towards the goal and re-plan later

Planning during Execution

- Planning is a repeated process!
  - partially-known environments → *edgecost changes*
  - dynamic environments → *edgecost changes, goal changes*
  - imperfect execution of plans → *robot pose changes/deviates off the path*
  - imprecise localization → *robot pose changes/deviates off the path*

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Only Goal Changes

Any ideas how to handle it?

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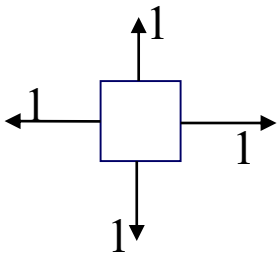
*Re-compute heuristics with respect to the **new** goal, and continue searching until the **new** goal state is expanded*

Only Goal Changes

- Example on the board!

$$h(\text{cell } \langle x,y \rangle) = |x - x_{goal}| + |y - y_{goal}| \text{ (Manhattan Distance)}$$

4-connected grid



robot

goal during 1st planning

	A	B	C	D	E
1	h=5	h=4	h=3	h=2	h=1
2	h=4	h=3	h=2		h=0
3	h=5	h=4	h=3	h=2	h=1
4	h=6	h=5	h=4	h=3	h=2

robot

goal during 2nd planning

	A	B	C	D	E
1	h=6	h=5	h=4	h=3	h=2
2	h=5	h=4	h=3		h=1
3	h=4	h=3	h=2	h=1	h=0
4	h=5	h=4	h=3	h=2	h=1

Only Robot Pose Changes

Any ideas how to handle it?

Only Robot Pose Changes

Any ideas how to handle it?

Do the search backwards:

Then, the problem becomes "Only Goal Changes" that we know how to solve already

What if both Robot Pose and its Goal change?

Too bad!
Typically, you are better of re-planning from scratch then.

Changes to Edgecosts

- Two main reasons
  - Noisy perception (e.g., flickering obstacles, sensed position of obstacles is shifting, robot localization is noisy, etc.)
  - Partially-known environment

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Typically, it is important to do clever filtering to minimize flicker as much as possible without sacrificing safety

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What should we assume about unknown space?

Changes to Edgecosts

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Typically, it is important to do clever filtering to minimize flicker as much as possible without sacrificing safety

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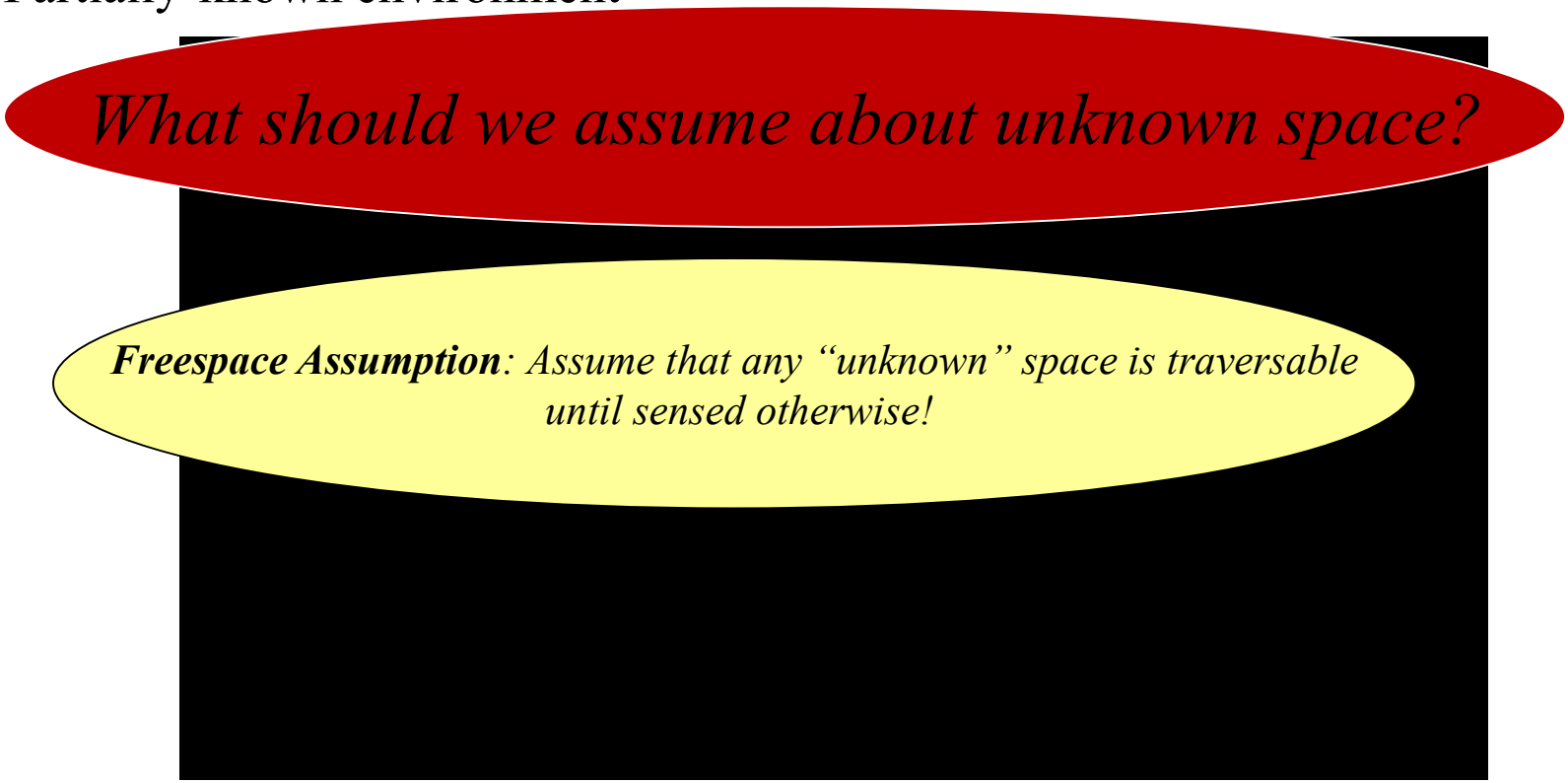
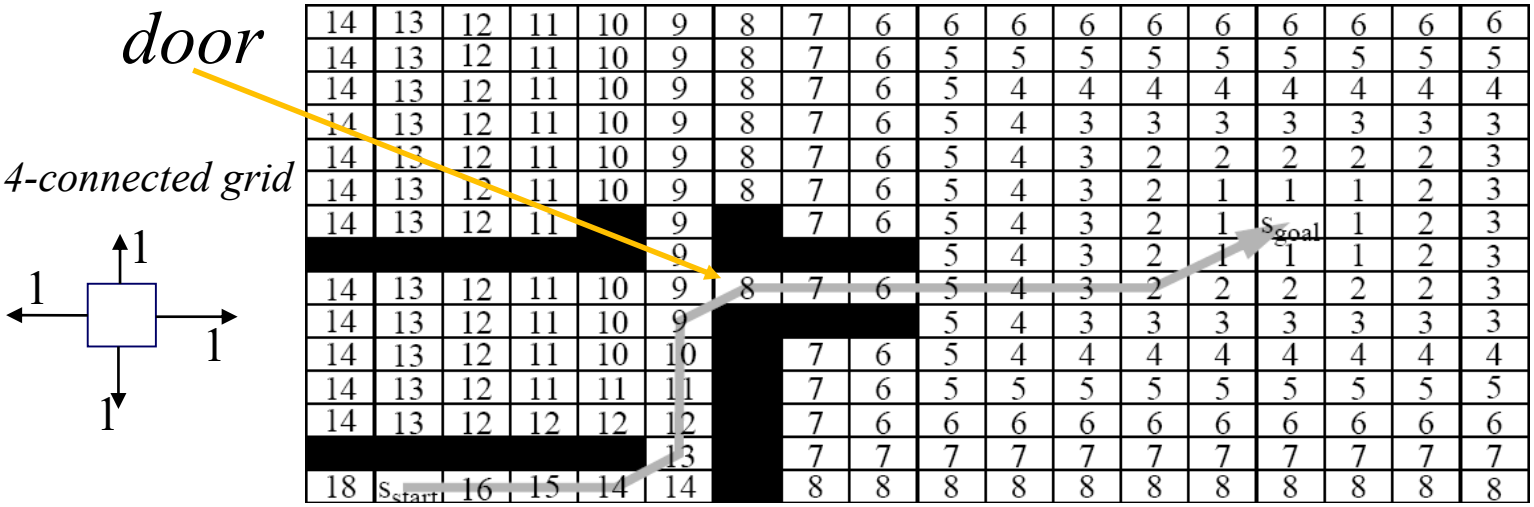


Changes to Edgecosts

- The robot doesn't initially know the status of the door



14	13	12	11	10	9	8	7	6	6	6	6	6	6	6	6	6	6
14	13	12	11	10	9	8	7	6	5	5	5	5	5	5	5	5	5
14	13	12	11	10	9	8	7	6	5	4	4	4	4	4	4	4	4
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14	13	12	11		9		7	6	5	4	3	2	1	s_{goal}	1	2	3
					9				5	4	3	2	1	1	1	2	3
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14	13	12	11	10	9				5	4	3	3	3	3	3	3	3
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14	13	12	11	11	11		7	6	5	5	5	5	5	5	5	5	5
14	13	12	12	12	12		7	6	6	6	6	6	6	6	6	6	6
					13		7	7	7	7	7	7	7	7	7	7	7
18	s_{start}	16	15	14	14		8	8	8	8	8	8	8	8	8	8	8

We ran an uninformed A search backwards (that is, all g-values are costs to s_{goal})*

Changes to Edgecosts

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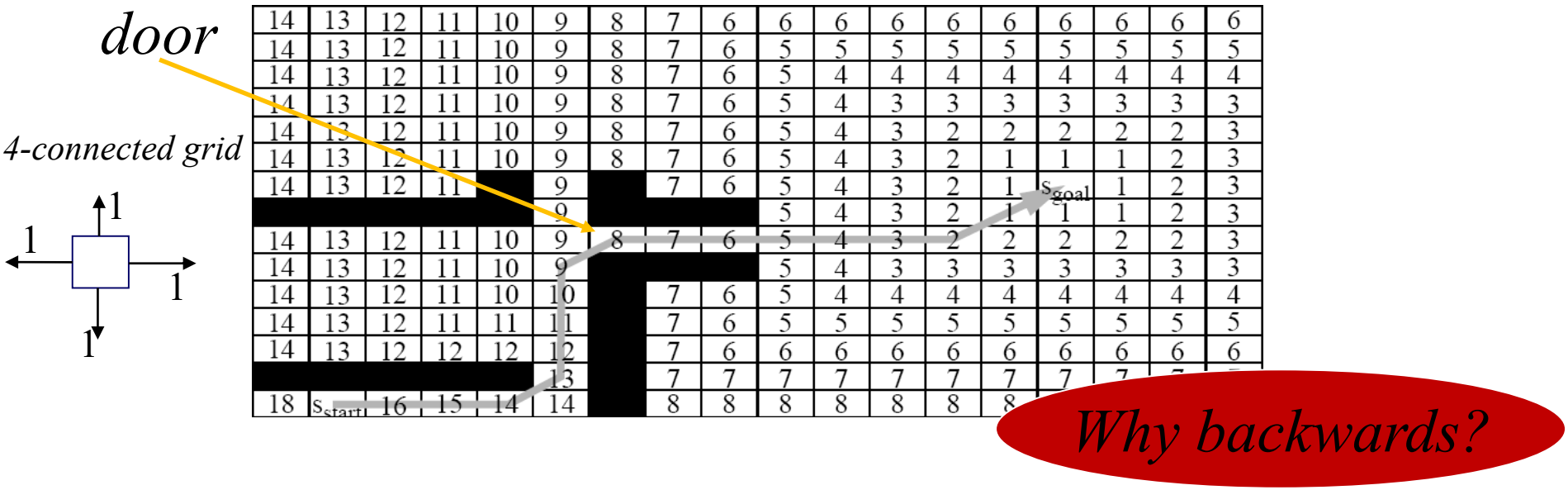

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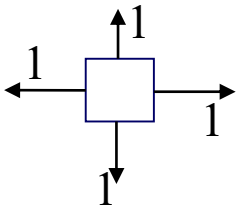

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14	13	12	11	10	9	8	7	6	5	5	5	5	5	5	5	5	5
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14	13	12	11	10	10	■	7	6	5	4	4	4	4	4	4	4	4
14	13	12	11	11	11	■	7	6	5	5	5	5	5	5	5	5	5
14	13	12	12	12	12	■	7	6	6	6	6	6	6	6	6	6	6
■	■	■	■	■	13	■	7	7	7	7	7	7	7	7	7	7	7
18	s_{start}	16	15	14	14	■	8	8	8	8	8	8	8	8	8	8	8

States with changed g-values

during execution, the robot found out that the door is closed

14	13	12	11	10	9	8	7	6	6	6	6	6	6	6	6	6	6
14	13	12	11	10	9	8	7	6	5	5	5	5	5	5	5	5	5
14	13	12	11	10	9	8	7	6	5	4	4	4	4	4	4	4	4
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15	14	13	12	11	11	■	7	6	5	4	3	2	2	2	2	2	3
15	14	13	12	12	s_{start}	■	■	■	5	4	3	3	3	3	3	3	3
15	14	13	13	13	13	■	7	6	5	4	4	4	4	4	4	4	4
15	14	14	14	14	14	■	7	6	5	5	5	5	5	5	5	5	5
15	15	15	15	15	15	■	7	6	6	6	6	6	6	6	6	6	6
■	■	■	■	■	16	■	7	7	7	7	7	7	7	7	7	7	7
21	20	19	18	17	17	■	8	8	8	8	8	8	8	8	8	8	8

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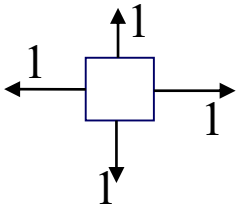
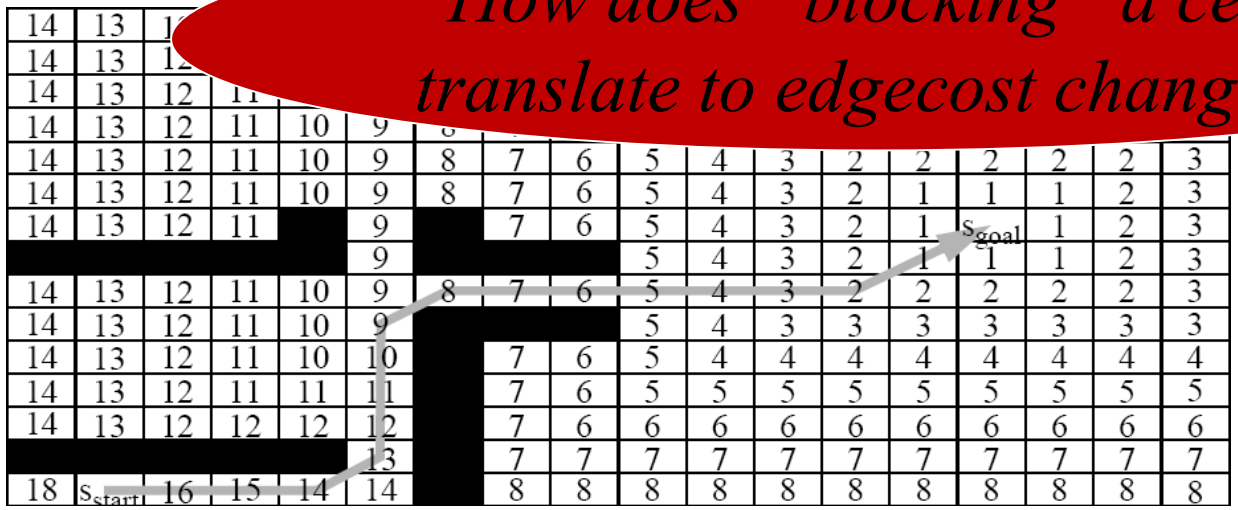
How does "blocking" a cell translate to edgecost changes?

4-connected grid





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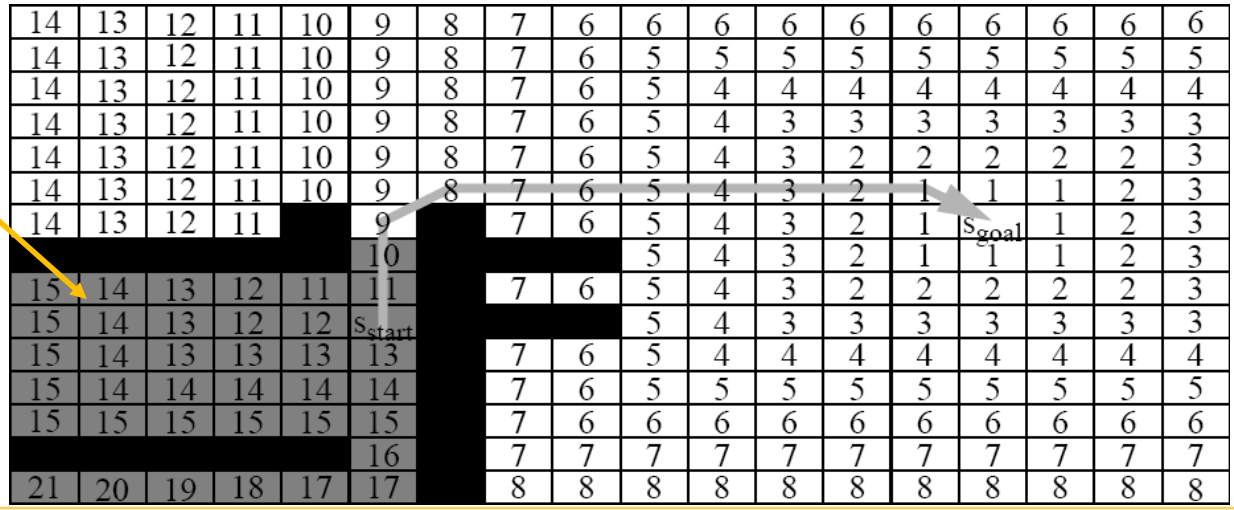

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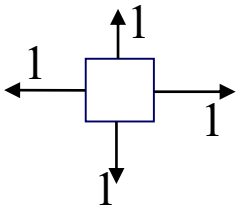

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14	13	12	11	11	11	■	7	6	5	5	5	5	5	5	5	5	5
14	13	12	12	12	12	■	7	6	6	6	6	6	6	6	6	6	6
■	■	■	■	■	13	■	7	7	7	7	7	7	7	7	7	7	7
18	s_{start}	16	15	14	14	■	8	8	8	8	8	8	8	8	8	8	8

States with changed g-values

during execution, the robot fo

*Can we reuse these g-values from one search to another? – incremental A**

14	13	12	11	10	9	8	7	6	6								
14	13	12	11	10	9	8	7	6	5	5	5	5					
14	13	12	11	10	9	8	7	6	5	4	4	4	4	4	4	4	4
14	13	12	11	10	9	8	7	6	5	4	3	3	3	3	3	3	3
14	13	12	11	10	9	8	7	6	5	4	3	2	2	2	2	2	3
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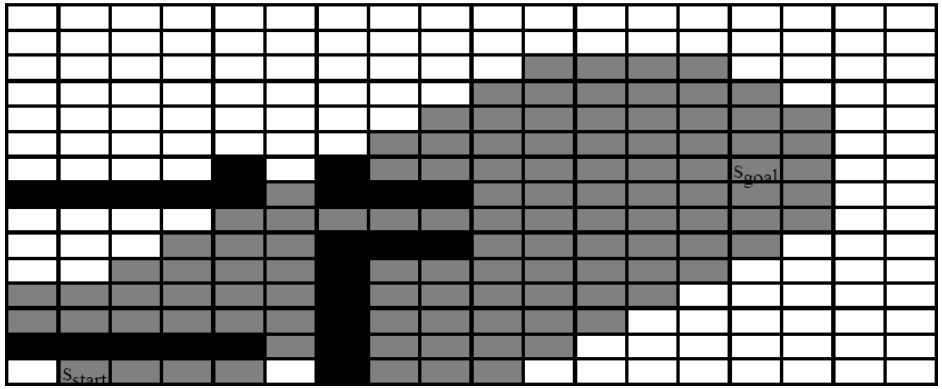
■	■	■	■	■	10	■	■	■	5	4	3	2	1	1	1	2	3
15	14	13	12	11	11	■	7	6	5	4	3	2	2	2	2	2	3
15	14	13	12	12	s_{start}	■	■	■	5	4	3	3	3	3	3	3	3
15	14	13	13	13	13	■	7	6	5	4	4	4	4	4	4	4	4
15	14	14	14	14	14	■	7	6	5	5	5	5	5	5	5	5	5
15	15	15	15	15	15	■	7	6	6	6	6	6	6	6	6	6	6
■	■	■	■	■	16	■	7	7	7	7	7	7	7	7	7	7	7
21	20	19	18	17	17	■	8	8	8	8	8	8	8	8	8	8	8

Incremental Heuristic Search

- D*/D* Lite: Incremental Heuristic Search Algorithms

*initial search by backwards A**



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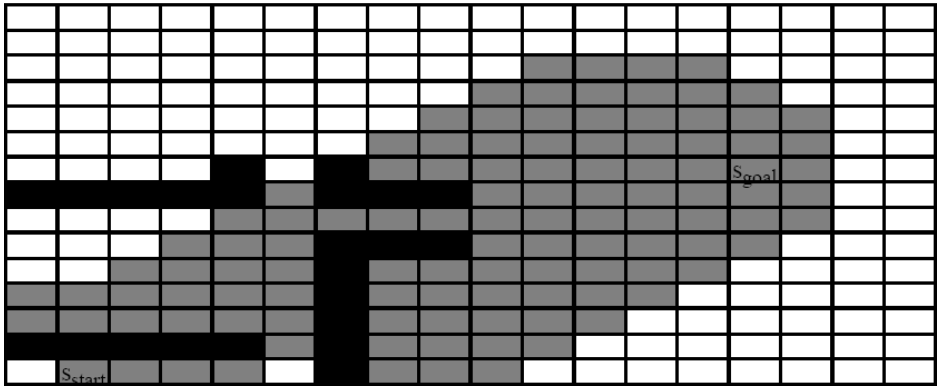
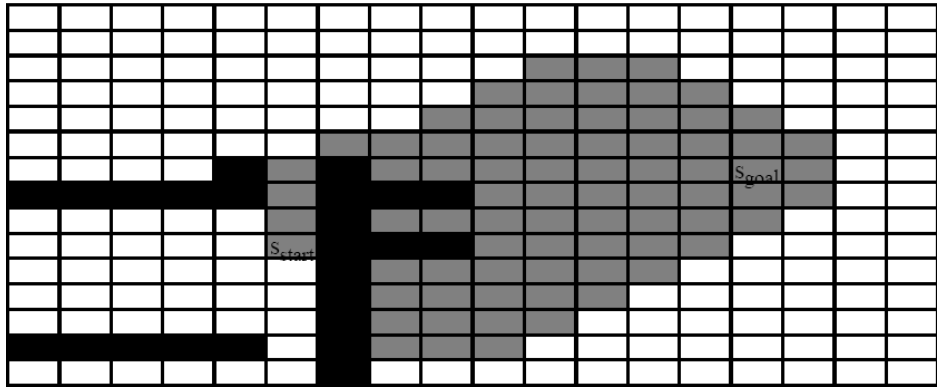
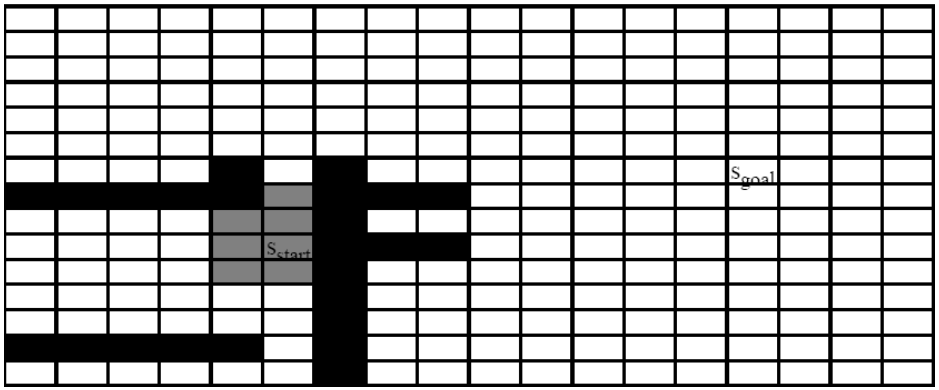


*second search by backwards A**

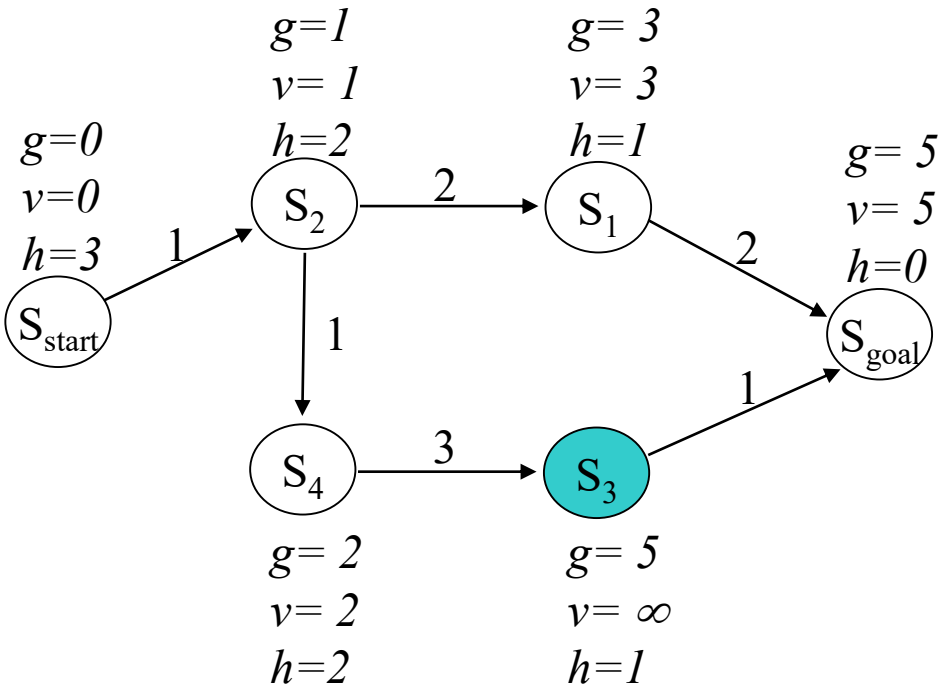


second search by D Lite*



A* with Reuse of State Values

- So far, ComputePathwithReuse() could only deal with states whose $v(s) \geq g(s)$ (overconsistent or consistent)
- Edge cost increases may introduce underconsistent states (v(s) < g(s))



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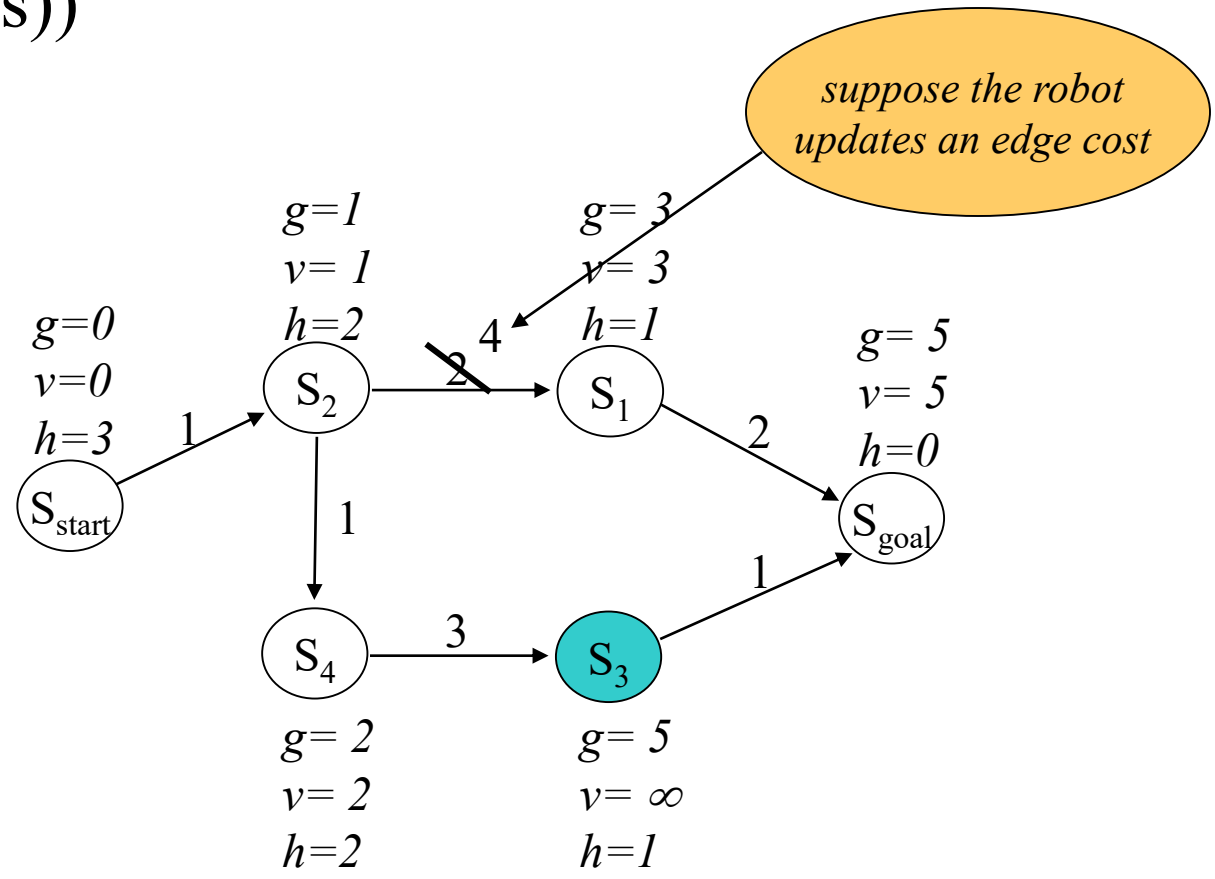

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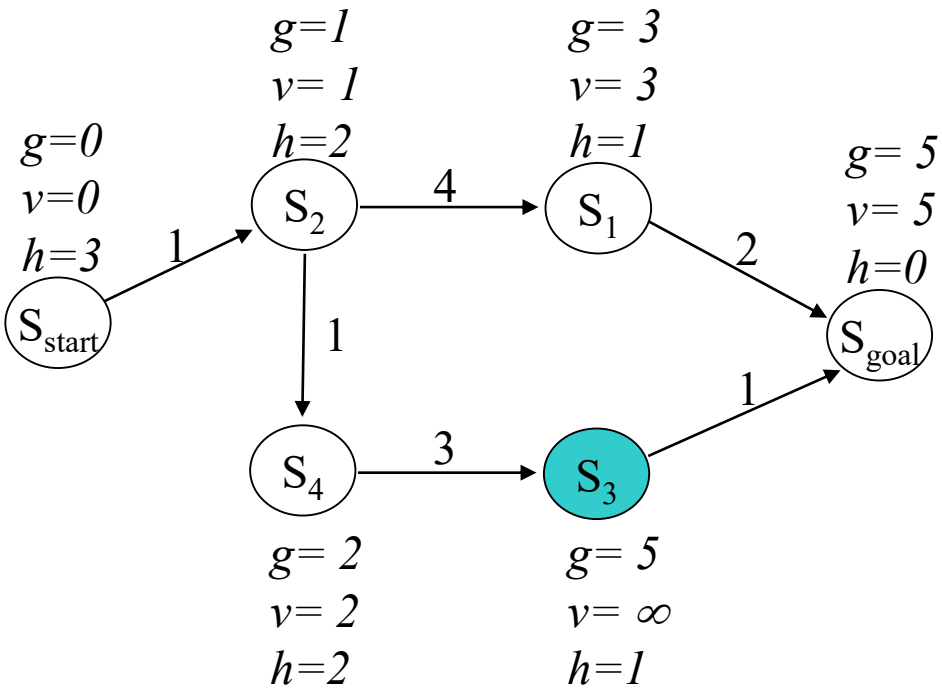
ComputePathwithReuse invariant:
$g(s') = \min_{s'' \in pred(s')} v(s'') + c(s'',s')$

↓

need to update $g(s_1)$



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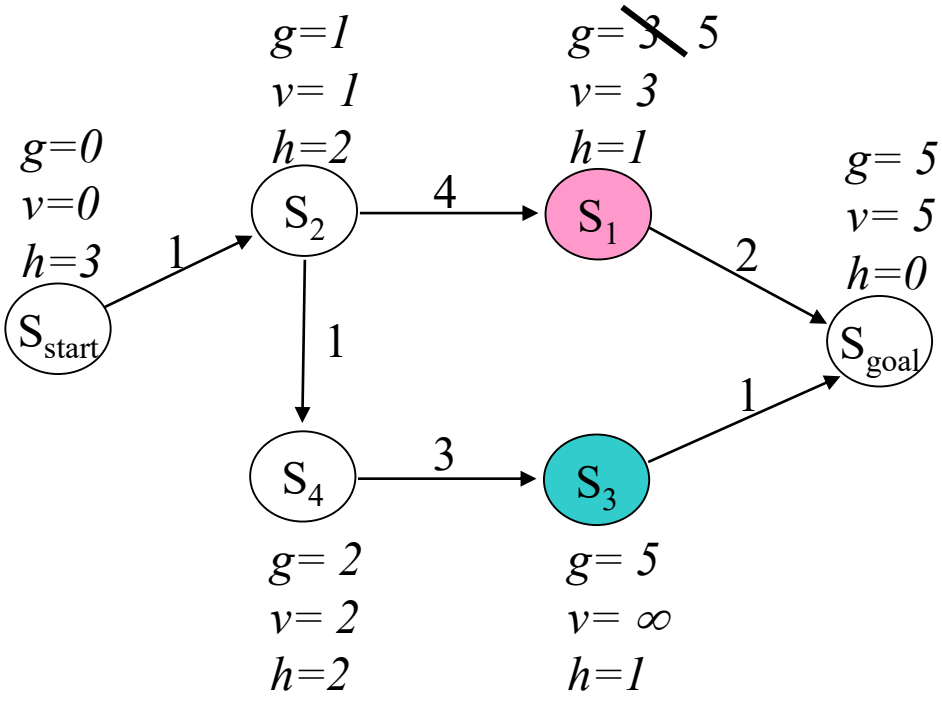

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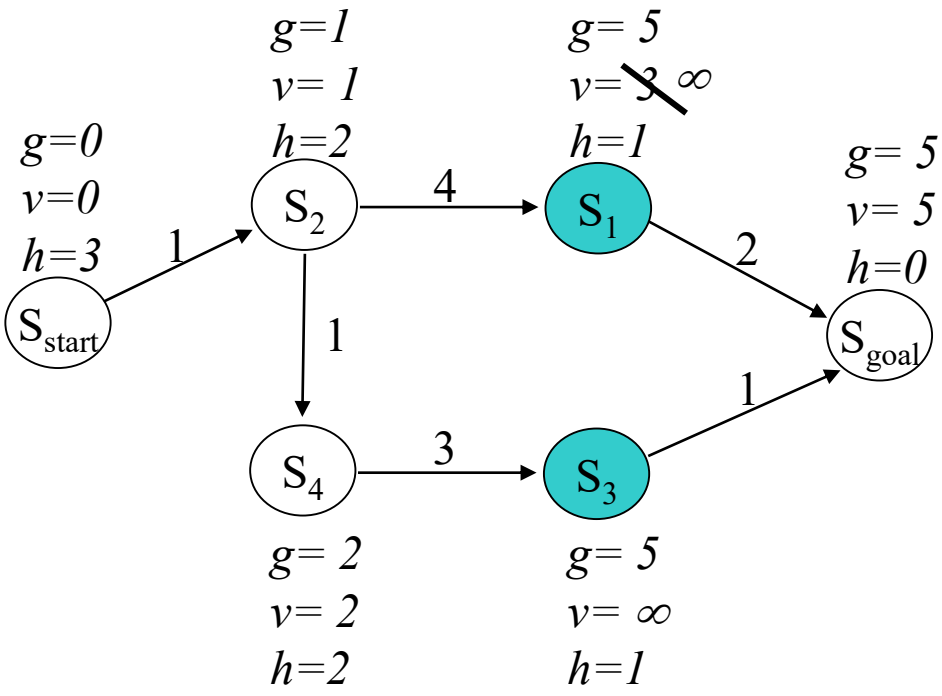

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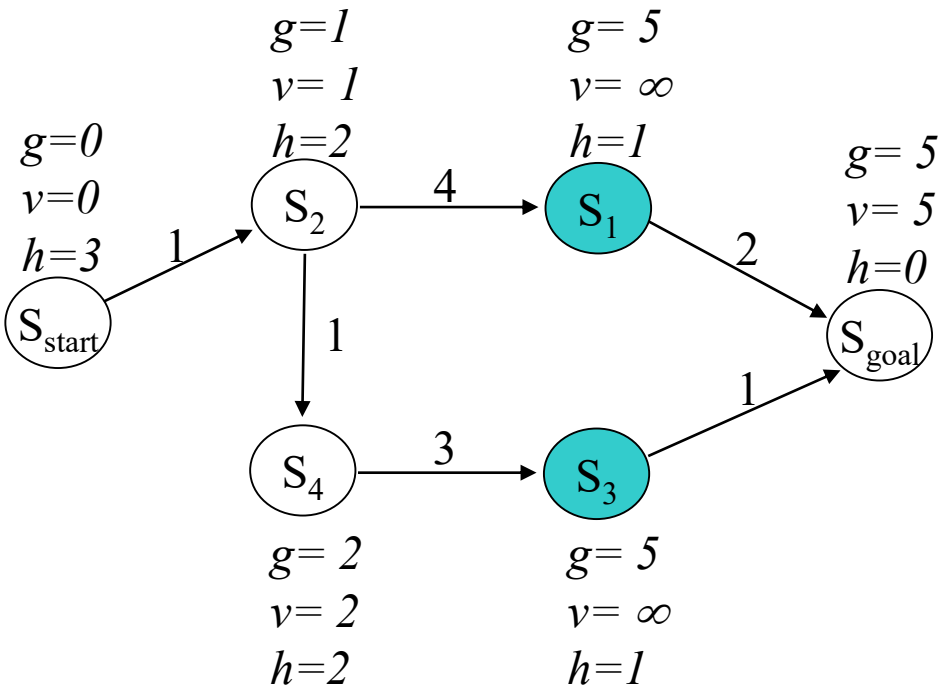

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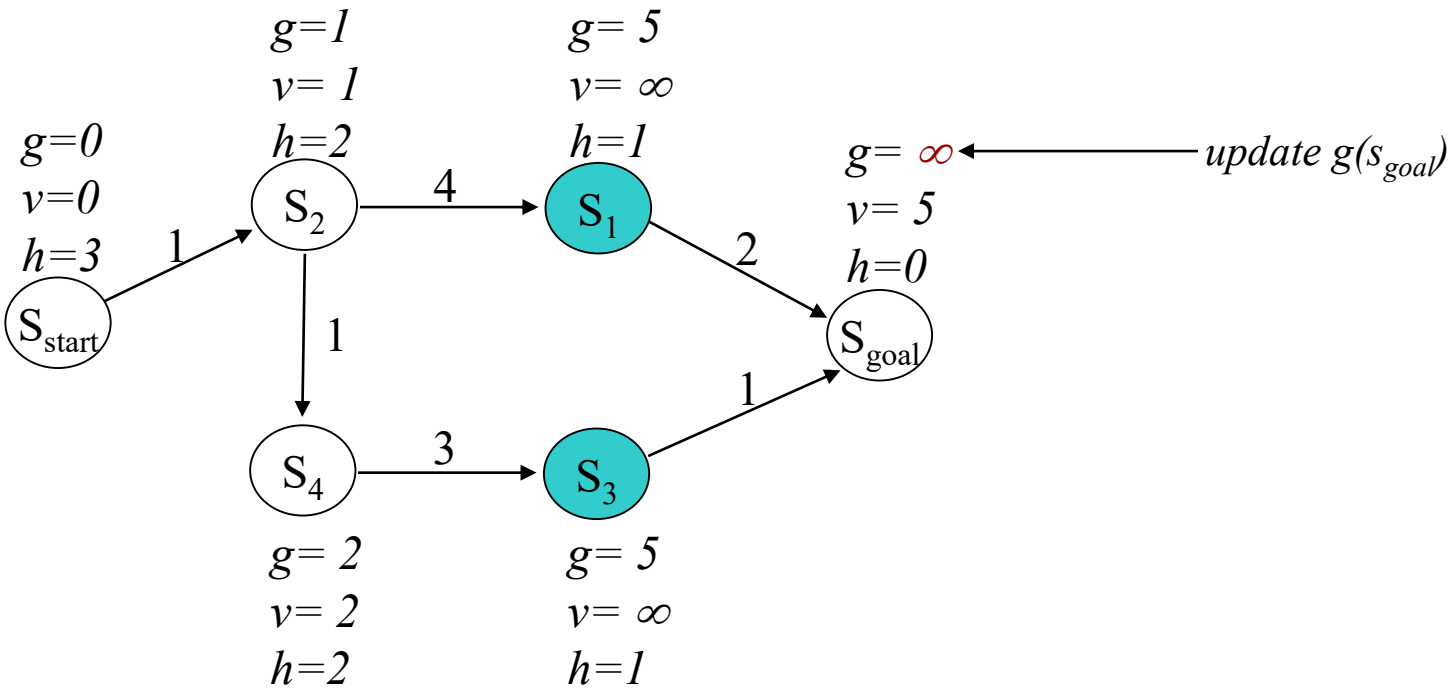

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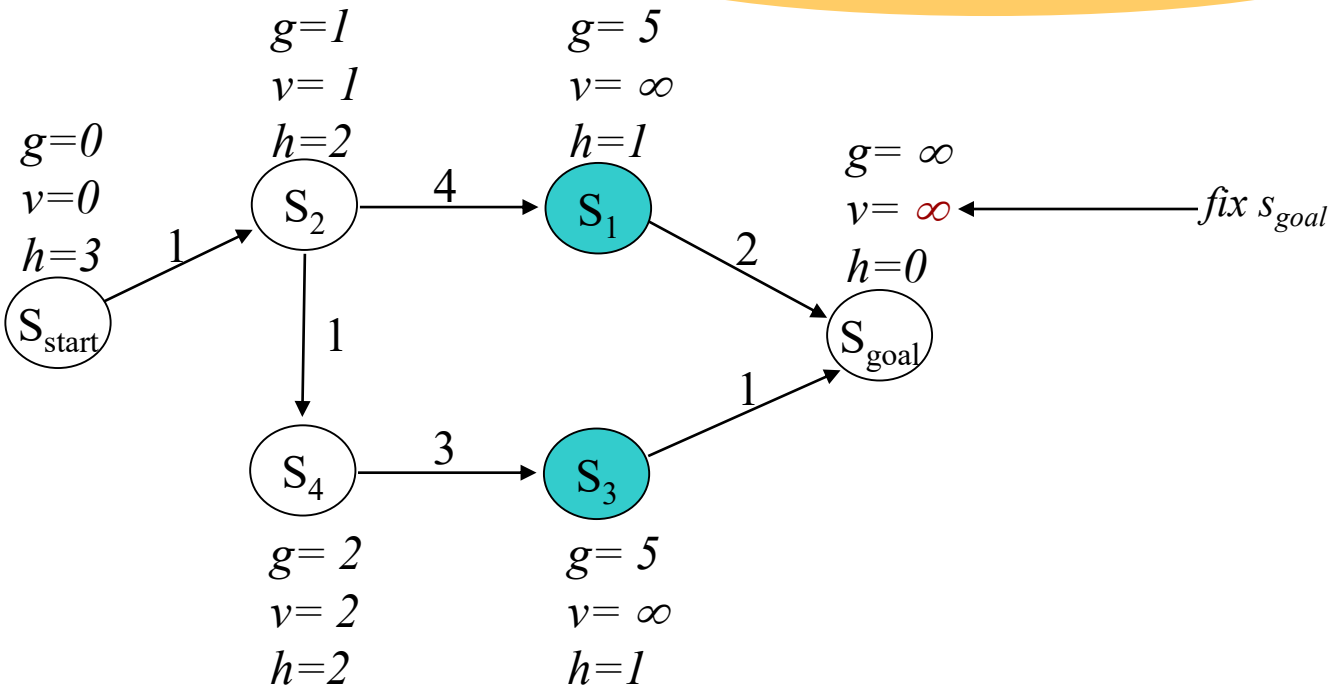

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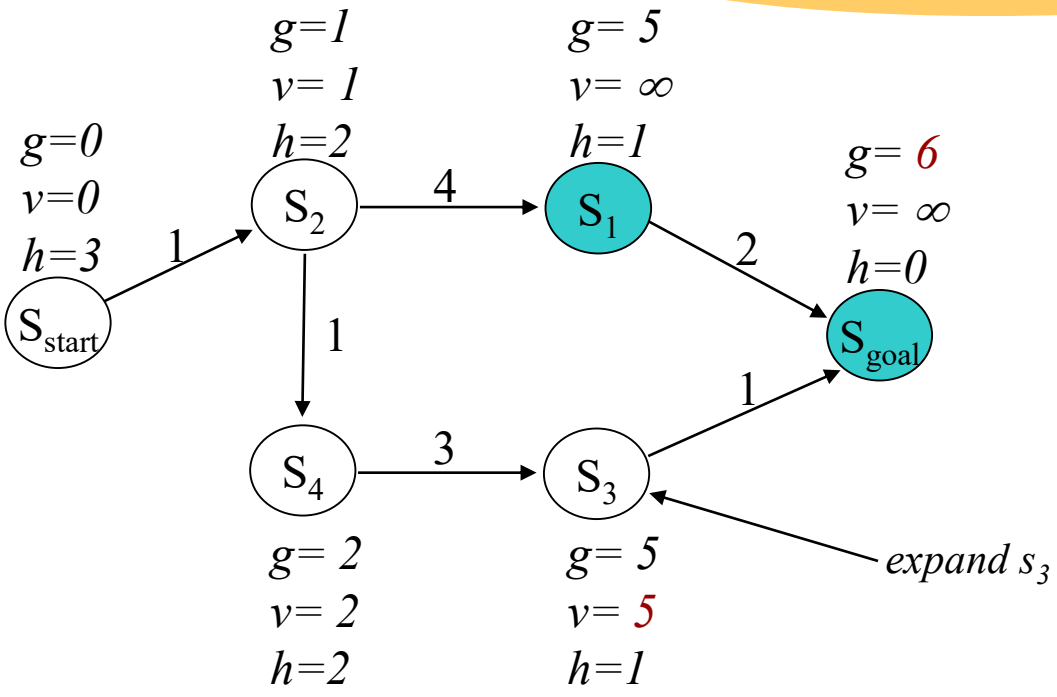

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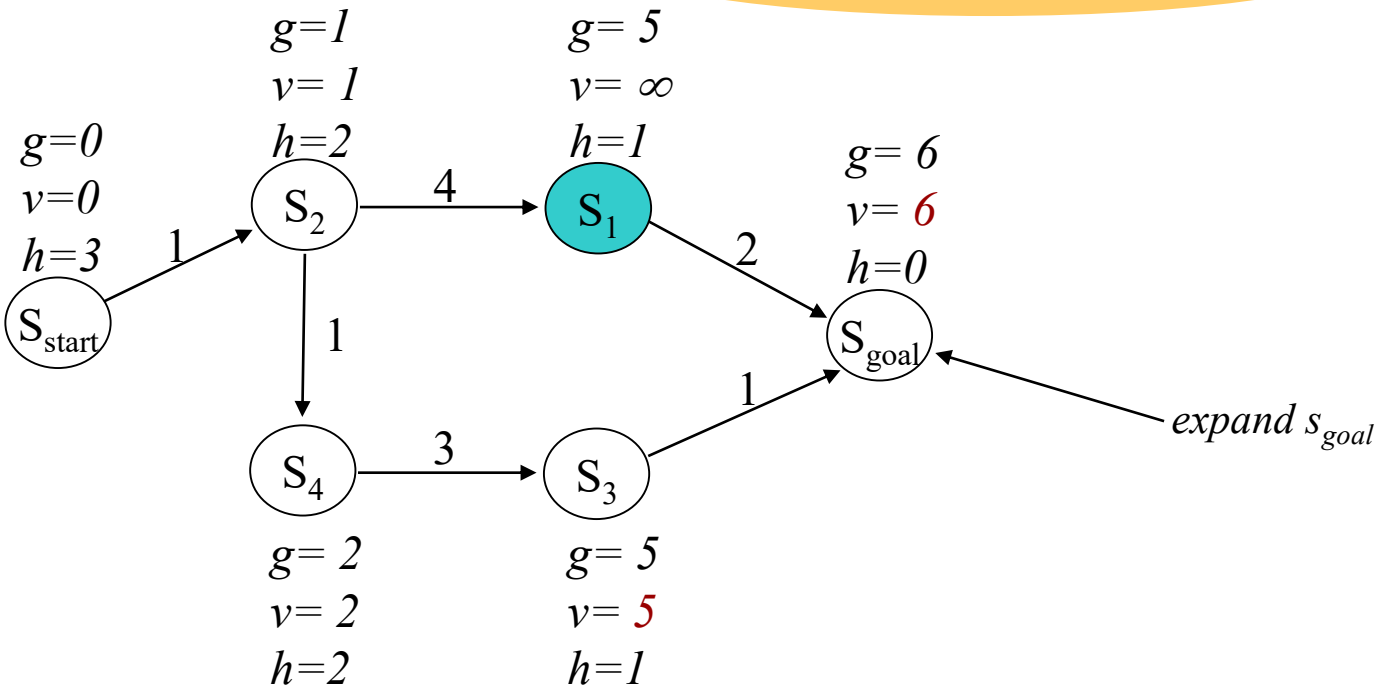

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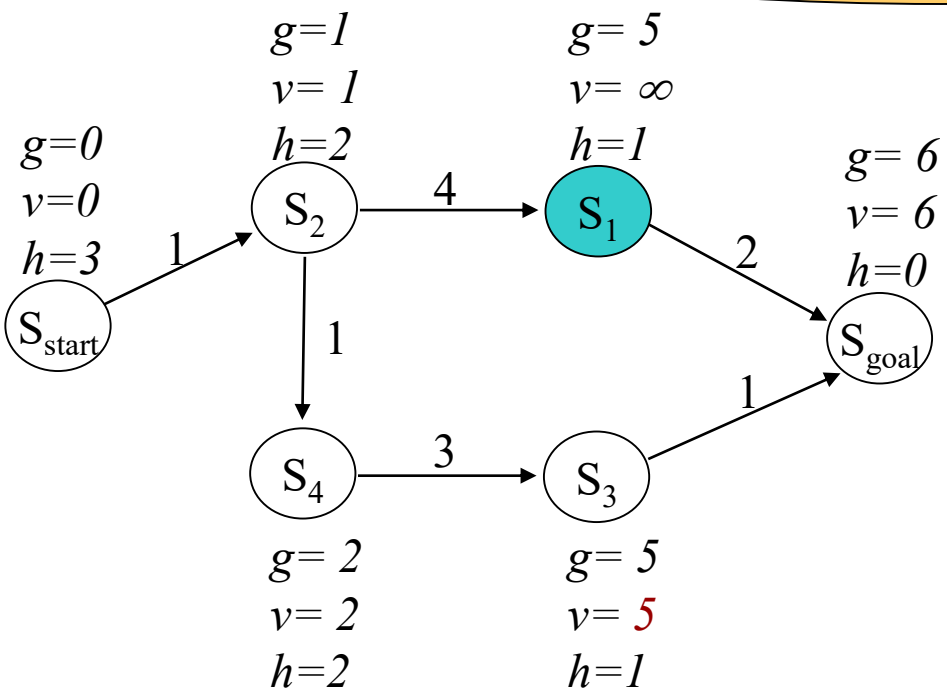
after ComputePathwithReuse terminates:
all g-values of states are equal to final A g-values*

we can backtrack an optimal path
(start at s_{goal}, proceed to pred that minimizes g+c)

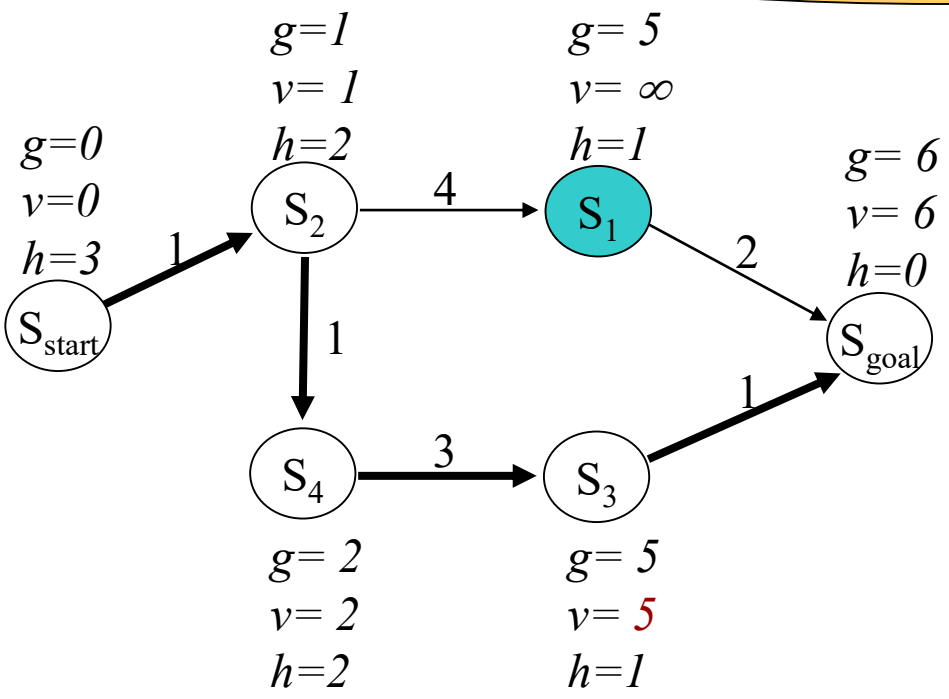


A* with Reuse of State Values

- Edge cost increases may introduce underconsistent states (v(s) < g(s))
- Fix these by setting $v(s) = \infty$
- Makes *s* overconsistent or consistent
- Propagate the changes

after ComputePathwithReuse terminates:
all g-values of states are equal to final A g-values*

we can backtrack an optimal path
(start at s_{goal}, proceed to pred that minimizes g+c)



D* Lite

- Optimal re-planning algorithm
- Simpler and with nicer theoretical properties version of D*

until goal is reached
    ComputePathwithReuse(); *//modified to fix underconsistent states*
    publish optimal path;
    follow the path until map is updated with new sensor information;
    update the corresponding edge costs;
    set s_{start} to the current state of the agent;

Anytime Incremental Heuristic Search

- Anytime D*:
  - decrease ε and update edge costs at the same time
  - re-compute a path by reusing previous state-values

set ε to large value;
until goal is reached
    ComputePathwithReuse(); *//modified to fix underconsistent states*
    publish ε-suboptimal path;
    follow the path until map is updated with new sensor information;
    update the corresponding edge costs;
    set s_{start} to the current state of the agent;
    if significant changes were observed
        increase ε or replan from scratch;
    else
        decrease ε;

What for?

Summary

- Changes to Start Only or Goal Only can be handled easily by continuing the search until “goal of the search” is expanded
- Freespace Assumption: assume that unknown is traversable until detected otherwise
- D*/D* Lite: Incremental versions of heuristic search (don’t need to know the exact algorithm)