# Incremental Path Planning

Continuous Planning and Dynamic A*

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16.412/6.834 Cognitive Robotics
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## Outline

- Optimal Path Planning in Partially Known Environments.
- Continuous Optimal Path Planning
  - Dynamic A*
  - Incremental A* (LRTA*) [Appendix]

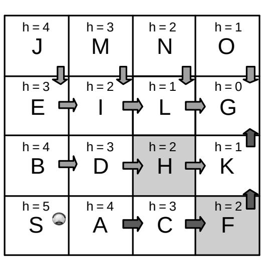
## [Zellinsky, 92]

1. Generate global path plan from initial map.
2. Repeat until goal reached or failure:
   - Execute next step in current global path plan
   - Update map based on sensors.
   - If map changed generate new global path from map.

## Compute Optimal Path

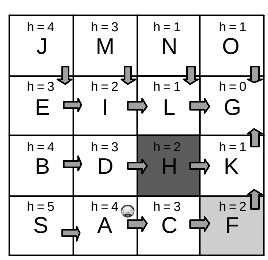
| | | | |
|---|---|---|---|
| J | M | N | O |
| E | I | L | G |
| B | D | H | K |
| S | A | C | F |

## Begin Executing Optimal Path



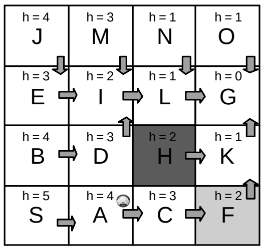

- Robot moves along backpointers towards goal.
- Uses sensors to detect discrepancies along way.

## Obstacle Encountered!



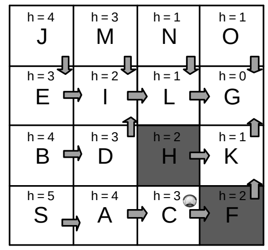

- At state A, robot discovers edge from D to H is blocked (cost 5,000 units).
- Update map and reinvoke planner.

## Continue Path Execution



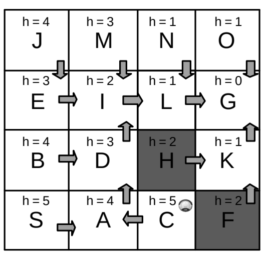

- A's previous path is still optimal.
- Continue moving robot along back pointers.

## Second Obstacle, Replan!




- At C robot discovers blocked edges from C to F and H (cost 5,000 units).
- Update map and reinvoke planner.

## Path Execution Achieves Goal




- Follow back pointers to goal.
- No further discrepancies detected; goal achieved!

## Outline

- Optimal Path Planning in Partially Known Environments.
- Continuous Optimal Path Planning
  - Dynamic A*
  - Incremental A* (LRTA*) [Appendix]

## What is Continuous Optimal Path Planning?

- Supports search as a repetitive online process.
- Exploits similarities between a series of searches to solve much faster than solving each search starting from scratch.
- Reuses the identical parts of the previous search tree, while updating differences.
- Solutions guaranteed to be optimal.
- On the first search, behaves like traditional algorithms.
  - D* behaves exactly like Dijkstra's.
  - Incremental A* A* behaves exactly like A*.

## Dynamic A* (aka D*) [Stenz, 94]

1. Generate global path plan from initial map.
2. Repeat until Goal reached, or failure.
   - Execute next step of current global path plan.
   - Update map based on sensor information.
   - Incrementally update global path plan from map changes.

➔ 1 to 3 orders of magnitude speedup relative to a non-incremental path planner.

## Map and Path Concepts

- *c(X,Y) :*
  Cost to move from Y to X.
  c(X,Y) is undefined if move disallowed.
- *Neighbors(X)* :
  Any Y such that c(X,Y) or c(Y,X) is defined.
- *o(G,X)* :
  True optimal path cost to Goal from X.
- *h(G,X)* :
  Estimate of optimal path cost to goal from X.
- *b(X) = Y : backpointer* from X to Y.
  Y is the first state on path from X to G.

## D* Search Concepts

- *State tag t(X)* :
  - *NEW* : has no estimate h.
  - *OPEN* : estimate needs to be propagated.
  - *CLOSED* : estimate propagated.
- *OPEN list* :
  States with estimates to be propagated to other states.
  - States on list tagged OPEN
  - Sorted by key function k (defined below).

## D* Fundamental Search Concepts

- k(G,X) : key function

  Minimum of
  - h(G,X) before modification, and
  - all values assumed by h(G,X) since X was placed on the OPEN list.
- *Lowered state* : k(G,X) = current h(G,X),
  - Propagate decrease to descendants and other nodes.
- *Raised state* : k(G,X) < current h(G,X),
  - Propagate increase to dscendants and other nodes.
  - Try to find alternate shorter paths.

## Running D* First Time on Graph

Initially
- Mark G Open and Queue it
- Mark all other states New
- Run Process_States on queue until path found or empty.

When edge cost c(X,Y) changes
- If X is marked Closed, then
  - Update h(X)
  - Mark X open and queue with key h(X).

## Use D* to Compute Initial Path

| | | | |
|---|---|---|---|
| J NEW | M NEW | N NEW | O NEW |
| E NEW | I NEW | L NEW | G NEW |
| B NEW | D NEW | H NEW | K NEW |
| S NEW | A NEW | C NEW | F NEW |

States initially tagged NEW (no cost determined yet).

## Use D* to Compute Initial Path

| | | | |
|---|---|---|---|
| J NEW | M NEW | N NEW | O NEW |
| E NEW | I NEW | L NEW | h = 0 G OPEN |
| B NEW | D NEW | H NEW | K NEW |
| S NEW | A NEW | C NEW | F NEW |

| | OPEN List |
|---|---|
| 1 | (0,G) |
| | |

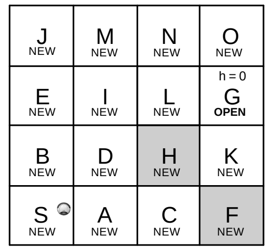
```
if kold = h(X) then
 for each neighbor Y of X:
  if t(Y) = NEW or
     (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
     (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
    b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Add Goal node to the OPEN list.
- Process OPEN list until the robot's current state is CLOSED.

## Process_State: New or Lowered State

- Remove from Open list , state X with lowest k
- If X is a new/lowered state, its path cost is optimal! Then propagate to each neighbor Y
  - If Y is New, give it an initial path cost and propagate.
  - If Y is a descendant of X, propagate any change.
  - Else, if X can lower Y's path cost, Then do so and propagate.

## Use D* to Compute Initial Path

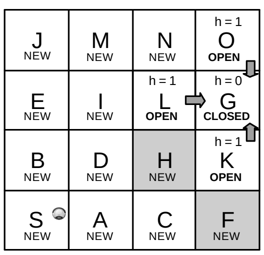



| | OPEN List |
|---|---|
| 1 | (0,G) |
| | |

```
if kold = h(X) then
  for each neighbor Y of X:
    if t(Y) = NEW or
      (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
      (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
      b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Add new neighbors of G onto the OPEN list
- Create backpointers to G.

## Use D* to Compute Initial Path

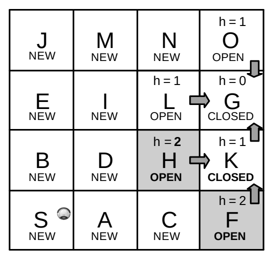



| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |

```
if kold = h(X) then
  for each neighbor Y of X:
    if t(Y) = NEW or
      (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
      (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
      b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Add new neighbors of G onto the OPEN list
- Create backpointers to G.

## Use D* to Compute Initial Path

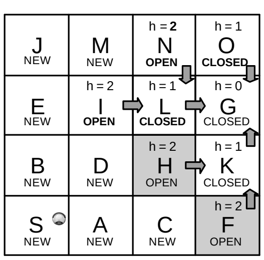



| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |

```
if kold = h(X) then
  for each neighbor Y of X:
    if t(Y) = NEW or
      (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
      (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
      b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Add new neighbors of K on to the OPEN list
- Create backpointers.

## Use D* to Compute Initial Path

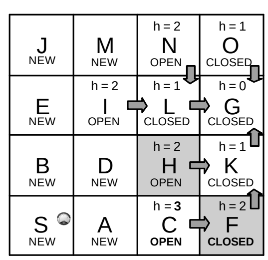



| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |
| 4 | (2,F) (2,H) (2,I) (2,N) |

```
if kold = h(X) then
  for each neighbor Y of X:
    if t(Y) = NEW or
      (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
      (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
      b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Add new neighbors of L, then O on to the OPEN list
- Create backpointers.

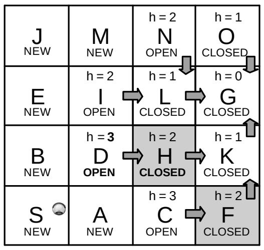
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |
| 4 | (2,F) (2,H) (2,I) (2,N) |
| 5 | (2,H) (2,I) (2,N) (3,C) |

- Continue until current state S is closed.

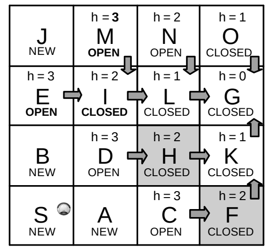
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |
| 4 | (2,F) (2,H) (2,I) (2,N) |
| 5 | (2,H) (2,I) (2,N) (3,C) |
| 6 | (2,I) (2,N) (3,C) (3,D) |

- Continue until current state S is closed.

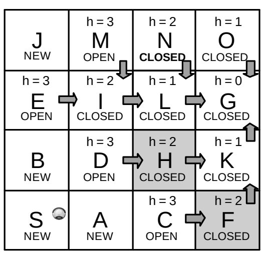
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |
| 4 | (2,F) (2,H) (2,I) (2,N) |
| 5 | (2,H) (2,I) (2,N) (3,C) |
| 6 | (2,I) (2,N) (3,C) (3,D) |
| 7 | (2,N) (3,C) (3,D) (3,E) (3,M) |

- Continue until current state S is closed.

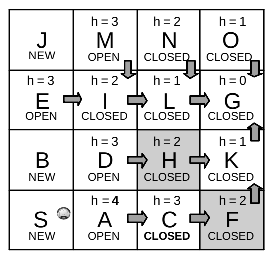
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |
| 4 | (2,F) (2,H) (2,I) (2,N) |
| 5 | (2,H) (2,I) (2,N) (3,C) |
| 6 | (2,I) (2,N) (3,C) (3,D) |
| 7 | (2,N) (3,C) (3,D) (3,E) (3,M) |
| 8 | (3,C) (3,D) (3,E) (3,M) |

- Continue until current state S is closed.

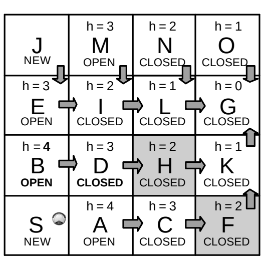
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |
| 4 | (2,F) (2,H) (2,I) (2,N) |
| 5 | (2,H) (2,I) (2,N) (3,C) |
| 6 | (2,I) (2,N) (3,C) (3,D) |
| 7 | (2,N) (3,C) (3,D) (3,E) (3,M) |
| 8 | (3,C) (3,D) (3,E) (3,M) |
| 9 | (3,D) (3,E) (3,M) (4,A) |

- Continue until current state S is closed.

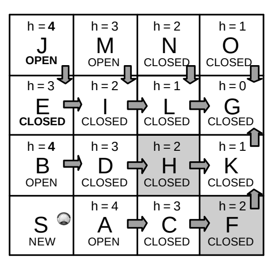
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 1 | (0,G) |
| 2 | (1,K) (1,L) (1,O) |
| 3 | (1,L) (1,O) (2,F) (2,H) |
| 4 | (2,F) (2,H) (2,I) (2,N) |
| 5 | (2,H) (2,I) (2,N) (3,C) |
| 6 | (2,I) (2,N) (3,C) (3,D) |
| 7 | (2,N) (3,C) (3,D) (3,E) (3,M) |
| 8 | (3,C) (3,D) (3,E) (3,M) |
| 9 | (3,D) (3,E) (3,M) (4,A) |
| 10 | (3,E) (3,M) (4,A) (4,B) |

- Continue until current state S is closed..

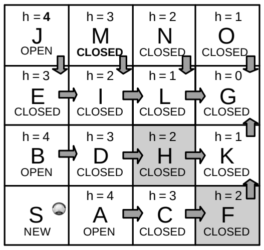
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 10 | (3,E) (3,M) (4,A) (4,B) |
| 11 | (3,M) (4,A) (4,B) (4,J) |
| 12 | |
| 13 | |
| 14 | |

- Continue until current state S is closed.

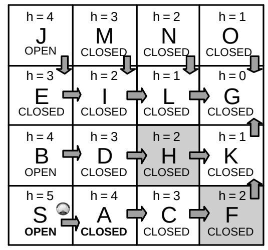
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 10 | (3,E) (3,M) (4,A) (4,B) |
| 11 | (3,M) (4,A) (4,B) (4,J) |
| 12 | (3,M) (4,A) (4,B) |
| 13 | |
| 14 | |

- Continue until current state S is closed.

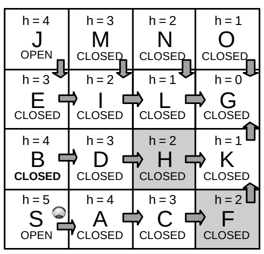
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 10 | (3,E) (3,M) (4,A) (4,B) |
| 11 | (3,M) (4,A) (4,B) (4,J) |
| 12 | (3,M) (4,A) (4,B) |
| 13 | (4,B) (4,J) (5,S) |
| 14 | |
| 15 | |

- Continue until current state S is closed.

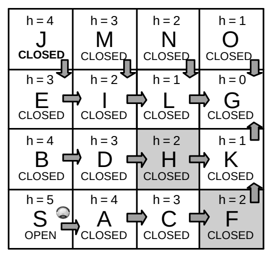
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 10 | (3,E) (3,M) (4,A) (4,B) |
| 11 | (3,M) (4,A) (4,B) (4,J) |
| 12 | (3,M) (4,A) (4,B) |
| 13 | (4,B) (4,J) (5,S) |
| 14 | (4,J) (5,S) |
| 15 | |

- Continue until current state S is closed.

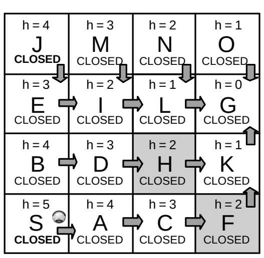
## Use D* to Compute Initial Path




| | OPEN List |
|---|---|
| 10 | (3,E) (3,M) (4,A) (4,B) |
| 11 | (3,M) (4,A) (4,B) (4,J) |
| 12 | (3,M) (4,A) (4,B) |
| 13 | (4,B) (4,J) (5,S) |
| 14 | (4,J) (5,S) |
| 15 | (5,S) |

- Continue until current state S is closed.

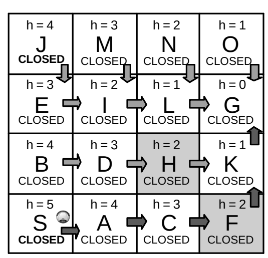
## D* Completed Initial Path




| | OPEN List |
|---|---|
| 10 | (3,E) (3,M) (4,A) (4,B) |
| 11 | (3,M) (4,A) (4,B) (4,J) |
| 12 | (3,M) (4,A) (4,B) |
| 13 | (4,B) (4,J) (5,S) |
| 14 | (4,J) (5,S) |
| 15 | (5,S) |
| 16 | NULL |

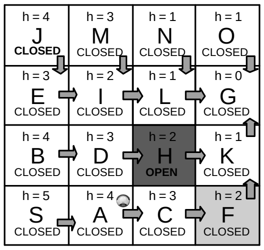
- Done: Current state S is closed, and Open list is empty.

## Begin Executing Optimal Path




- Robot moves along backpointers towards goal
- Uses sensors to detect discrepancies along way.

# Obstacle Encountered!



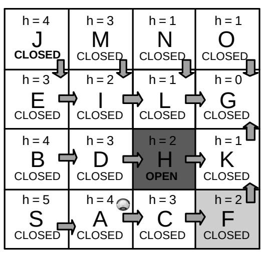

- At state A, robot discovers edge D to H is blocked off (cost 5,000 units).
- Update map and reinvoke D*

# Running D* After Edge Cost Change

When edge cost c(X,Y) changes

- If X is marked Closed, then
  - Update h(X)
  - Mark X open and queue, key is new h(X).
- Run Process_State on queue
  - until path to current state is shown optimal,
  - or queue Open List is empty.

# D* Update From First Obstacle

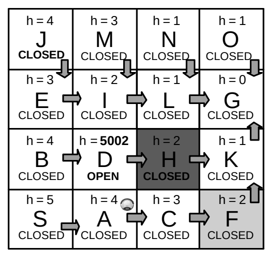



| | OPEN List |
|---|---|
| 1 | (2,H) |
| 2 | |
| 3 | |
| 4 | |

```
Function: Modify-Cost(X,Y,eval)
c(X,Y) = eval
if t(X) = CLOSED
   then Insert(X,h(X))
return Get-Kmin()
```

- Assign cost of 5,000 for D to H
- Propagate changes starting at H

# D* Update From First Obstacle




| | OPEN List |
|---|---|
| 1 | (2,H) |
| 2 | (3,D) |
| 3 | |
| 4 | |

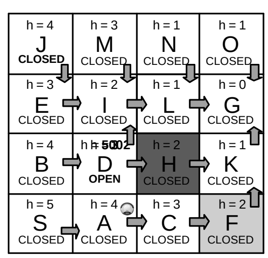
```
if kold = h(X) then
 for each neighbor Y of X:
  if t(Y) = NEW or
     (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
     (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
     b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Raise cost of H's descendant D, and propagate.

# Process_State: Raised State

- If X is a raise state its cost might be suboptimal.
- Try reducing cost of X using an *optimal neighbor* Y.
  - h(Y) = [h(X) before it was raised]
- Propagate X's cost to each neighbor Y
  - If Y is New, Then give it an initial path cost and propagate.
  - **If Y is a descendant of X, Then propagate ANY change.**
  - If X can lower Y's path cost,
    - Postpone: Queue X to propagate when optimal (reach current h(X))
  - If Y can lower X's path cost, and Y is suboptimal,
    - Postpone: Queue Y to propagate when optimal (reach current h(Y)).
  - ➔ Postponement avoids creating cycles.

# D* Update From First Obstacle

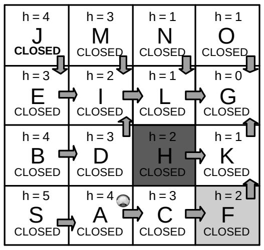



| | OPEN List |
|---|---|
| 1 | (2,H) |
| 2 | (3,D) |
| 3 | |
| 4 | |

```
if kold < h(X) then
 for each neighbor Y of X:
  if h(Y) = kold and h(X) > h(Y) + C(Y,X) then
    b(X) = Y; h(X) = h(Y) + c(Y,X);
```

- D may not be optimal, check neighbors for better path.
- Transitioning to I is better, and I's path is optimal, so update D.

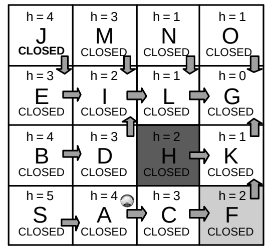
## D* Update From First Obstacle




| | OPEN List |
|---|---|
| 1 | |
| 2 | (3,D) |
| 3 | NULL |
| 4 | |

- All neighbors of D have consistent h-values.
- No further propagation needed.

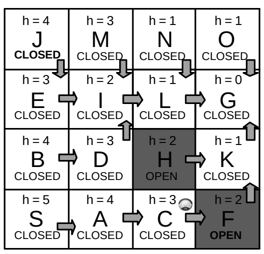
## Continue Path Execution




| | OPEN List |
|---|---|
| 1 | |
| 2 | (3,D) |
| 3 | NULL |
| 4 | |

- A's path optimal.
- Continue moving robot along backpointers.

## Second Obstacle!

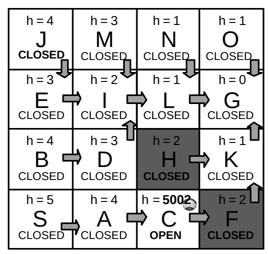



| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | |
| 3 | |
| 4 | |

```
Function: Modify-Cost(X,Y,eval)
1:  c(X,Y) = eval
2:  if t(X) = CLOSED
      then Insert(X,h(X))
3:  return Get-Kmin()
```

- At C robot discovers blocked edges C to F and H (cost 5,000 units).
- Update map and reinvoke D* until H(current position optimal).

## D* Update From Second Obstacle

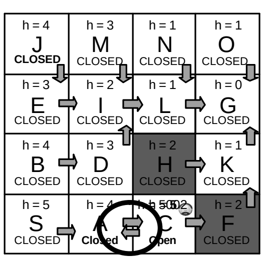



| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | (3,C) |
| 3 | |
| 4 | |

```
8:  if kold = h(X) then
9:   for each neighbor Y of X:
10:    if t(Y) = NEW or
11:       (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
12:       (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
13:       b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Processing F raises descendant C's cost, and propagates.
- Processing H does nothing.

## D* Update From Second Obstacle

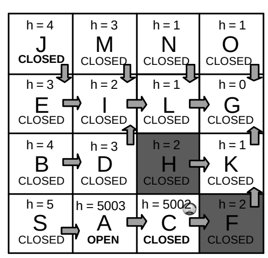



| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | (3,C) |
| 3 | |
| 4 | |

```
4:  if kold < h(X) then
5:   for each neighbor Y of X:
6:     if h(Y) = kold and h(X) > h(Y) + C(Y,X) then
7:      b(X) = Y; h(X) = h(Y) + c(Y,X);
```

- C may be suboptimal, check neighbors; ➔ Better path through A!
- However, A may be suboptimal, and updating would create a loop!

## D* Update From Second Obstacle




| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | (3,C) |
| 3 | (4,A) |
| 4 | |

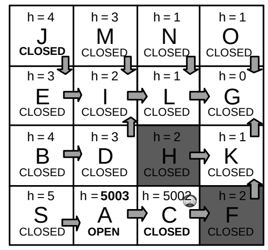
```
15:  for each neighbor Y of X:
16:   if t(Y) = NEW or
17:       (b(Y) = X and h(Y) ? h(X) + c(X,Y))
then
18:       b(Y) = X; Insert(Y,h(X) + c(X,Y))
```

- Don't change C's path to A (yet).
- Instead, propagate increase to A.

## Process_State: Raised State

- If X is a raise state its cost might be suboptimal.
- **Try reducing cost of X using an *optimal neighbor* Y.**
  - h(Y) = [h(X) before it was raised]
- propagate X's cost to each neighbor Y
  - If Y is New, Then give it an initial path cost and propagate.
  - **If Y is a descendant of X, Then propagate ANY change.**
  - If X can lower Y's path cost,
    - Postpone: Queue X to propagate when optimal (reach current h(X))
  - **If Y can lower X's path cost, and Y is suboptimal,**
    - **Postpone:** Queue Y to propagate when optimal (reach current h(Y)).
  - ➔ Postponement avoids creating cycles.

## D* Update From Second Obstacle

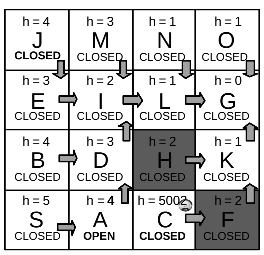



| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | (3,C) |
| 3 | (4,A) |
| 4 | |

```
if kold < h(X ) then
 for each neighbor Y of X:
   if h(Y) = kold and h(X) > h(Y) + C(Y,X) then
    b(X) = Y; h(X) = h(Y) + c(Y,X);
```

- A may not be optimal, check neighbors for better path.
- Transitioning to D is better, and D's path is optimal, so update A.

## D* Update From Second Obstacle




| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | (3,C) |
| 3 | (4,A) |
| 4 | |

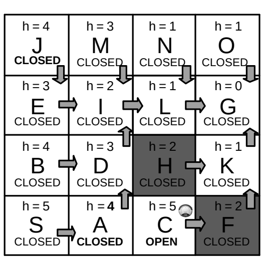
```
if kold < h(X ) then
 for each neighbor Y of X:
   if h(Y) = kold and h(X) > h(Y) + C(Y,X) then
    b(X) = Y; h(X) = h(Y) + c(Y,X);
```

- A may not be optimal, check neighbors for better path.
- Transitioning to D is better, and D's path is optimal, so update A.

## Process_State: New or Lowered State

- Remove from Open list , state X with lowest k
- If X is a new/lowered state its path cost is optimal, Then propagate to each neighbor Y
  - If Y is New, give it an initial path cost and propagate.
  - If Y is a descendant of X, propagate any change.
  - Else, if X can lower Y's path cost, Then do so and propagate.

## D* Update From Second Obstacle

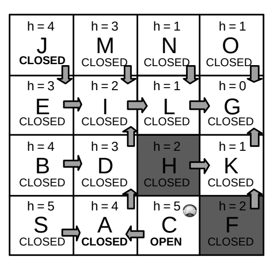



| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | (3,C) |
| 3 | (4,A) |
| 4 | (5,C) |

```
for each neighbor Y of X:
  if (b(Y) = X and h(Y) ? h(X) + c(X,Y)) then
    b(Y) = X; Insert(Y,h(X) + c(X,Y))
  else
     if b(Y) ? X and h(Y) > h(X) + c(X,Y) then
       Insert(X,h(X))
```

- A can improve neighbor C, so queue C.

## D* Update From Second Obstacle

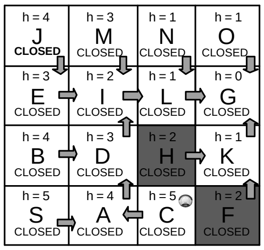



| | OPEN List |
|---|---|
| 1 | (2,F) (2,H) |
| 2 | (3,C) |
| 3 | (4,A) |
| 4 | (5,C) |
| 5 | |

```
if kold = h(X ) then
 for each neighbor Y of X:
  if t(Y ) = NEW or
     (b(Y ) = X and h(Y ) ? h(X ) + c(X,Y)) or
     (b(Y ) ? X and h(Y ) > h(X ) + c(X,Y)) then
     b(Y ) = X; Insert(Y,h(X ) + c(X,Y ))
```

- C lowered to optimal; no neighbors affected.
- Current state reached, so Process_State terminates.

## Complete Path Execution




- Follow back pointers to Goal.
- No further discrepancies detected; goal achieved!

## D* Pseudo Code

```
Function: Process-State()
  X = Min-State()
  if X=NULL then return -1
  kold = Get-Kmin(); Delete(X)
  if kold < h(X) then
   for each neighbor Y of X:
     if h(Y) = kold and h(X) > h(Y) + C(Y,X) then
      b(X) = Y; h(X) = h(Y) + c(Y,X);
  if kold = h(X) then
   for each neighbor Y of X:
     if t(Y) = NEW or
        (b(Y) = X and h(Y) ? h(X) + c(X,Y)) or
        (b(Y) ? X and h(Y) > h(X) + c(X,Y)) then
        b(Y) = X; Insert(Y,h(X) + c(X,Y))
 else
  for each neighbor Y of X:
    if t(Y) = NEW or
       (b(Y) = X and h(Y) ? h(X) + c(X,Y)) then
       b(Y) = X; Insert(Y,h(X) + c(X,Y))
    else
       if b(Y) ? X and h(X) > h(X) + c(X,Y) then
          Insert(X,h(X))
       else
         if b(Y) ? X and h(X) > h(Y) + c(Y,X) and
            t(Y) = CLOSED and h(Y) > kold then
            Insert(Y,h(Y))
 return Get-Kmin()
```

```
Function: Modify-Cost(X,Y,eval)
  c(X,Y) = eval
  if t(X) = CLOSED
     then Insert(X,h(X))
  return Get-Kmin()
```

```
Function: Insert(X, h_new)
  if t(X) = NEW
     then k(x) = h_new
  else if t(X) = OPEN
     then k(X) = min(k(X), h_new)
  else
     k(X) = min(h(X), h_new)
  h(X) = h_new;
  t(X) = OPEN
```

## Recap: Continuous Optimal Planning

1. Generate global path plan from initial map.
2. Repeat until Goal reached, or failure.
   - Execute next step of current global path plan.
   - Update map based on sensor information.
   - Incrementally update global path plan from map changes.

➔ 1 to 3 orders of magnitude speedup relative to a non-incremental path planner.

## Recap: Dynamic A*

- Supports search as a repetitive online process.
- Exploits similarities between a series of searches to solve much faster than from scratch.
- Reuses the identical parts of the previous search tree, while updating differences.
- Solutions guaranteed to be optimal.
- On the first search, behaves like traditional Dijkstra.