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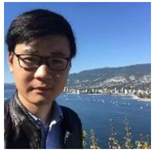
Lecture 2

SEARCH-BASED PATH FINDING



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Outline

1. Graph Search Basis
2. Dijkstra and A*
3. Jump Point Search
4. Homework

Graph Search Basis

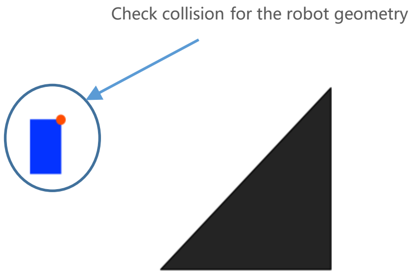
Configuration Space

Configuration Space

- **Robot configuration:** a specification of the positions of all points of the robot
- **Robot degree of freedom (DOF):** The minimum number n of real-valued coordinates needed to represent the robot configuration
- **Robot configuration space:** a n-dim space containing all possible robot configurations, denoted as C-space
- **Each robot pose is a point in the C-space**

Configuration Space Obstacle

- Planning in workspace
  - Robot has different shape and size
  - Collision detection requires knowing the robot geometry - time consuming and hard

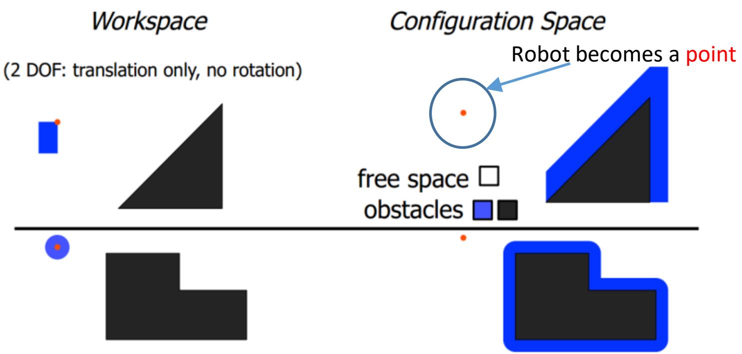


(1) Rectangular mobile robot

(2) Circular mobile robot

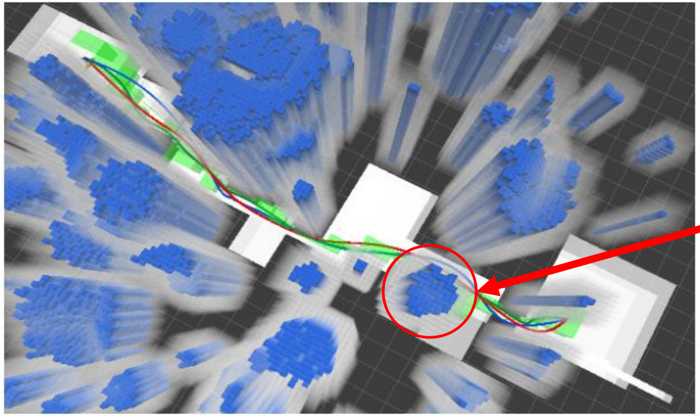
Configuration Space Obstacle

- Planning in configuration space
  - Robot is represented by a point in C-space, e.g. position (a point in R^3), pose (a point in $so(3)$),etc.
  - Obstacles need to be represented in configuration space (one-time work prior to motion planning), called configuration space obstacle, or C-obstacle
  - C-space = (C-obstacle) ∪ (C-free)
  - The path planning is finding a path between start point q_{start} and goal point q_{goal} within C-free



Workspace and Configuration Space Obstacle

- In workspace
  - Robot has shape and size (i.e. hard for motion planning)
- In configuration space: C-space
  - Robot is a point (i.e. easy for motion planning)
  - Obstacle are represented in C-space prior to motion planning
- Representing an obstacle in C-space can be extremely complicated. So approximated (but more conservative) representations are used in practice.



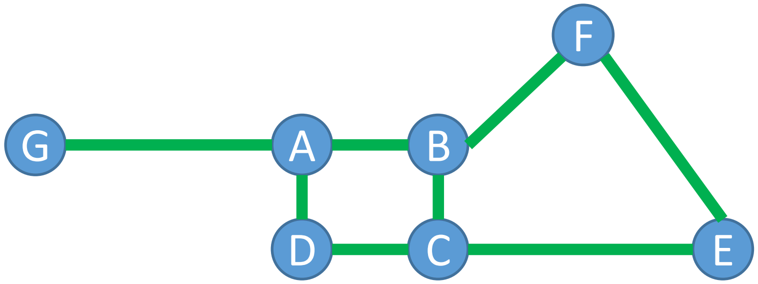
If we model the robot conservatively as a ball with radius δ_r, then the C-space can be constructed by inflating obstacle at all directions by δ_r.

Graph and Search Method

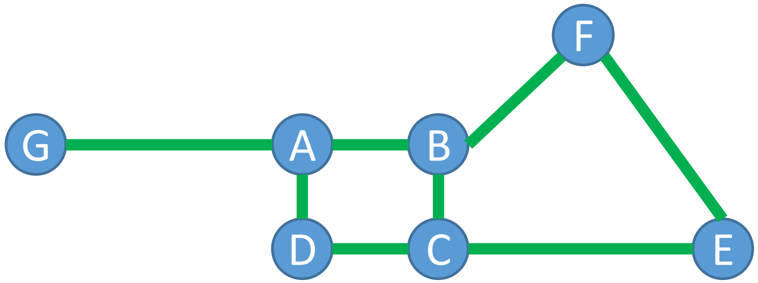
Search-based Method

Graphs

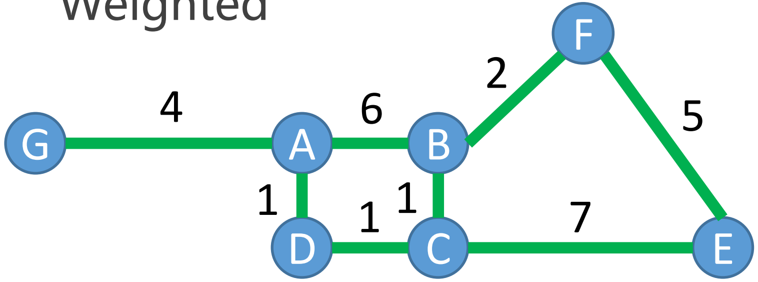
Graphs have nodes and edges



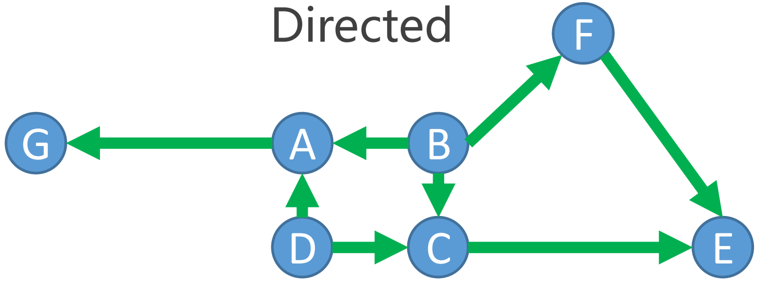
Undirected



Weighted

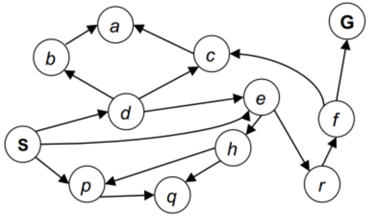


Directed

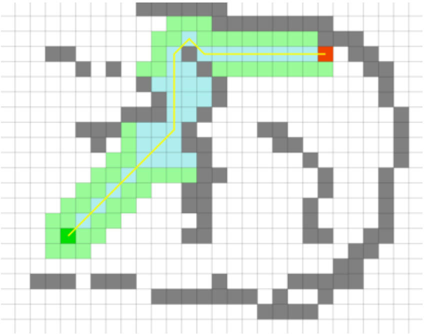


Search-based Method

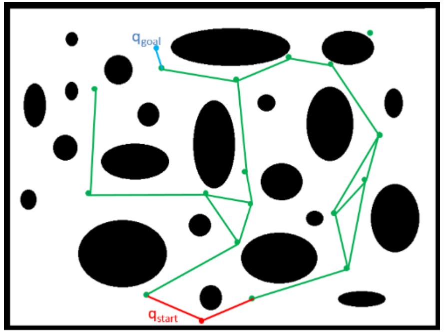
- State space graph: a mathematical representation of a search algorithm
  - For every search problem, there's a corresponding state space graph
  - Connectivity between nodes in the graph is represented by (directed or undirected) edges



Ridiculously tiny search graph for a tiny search problem



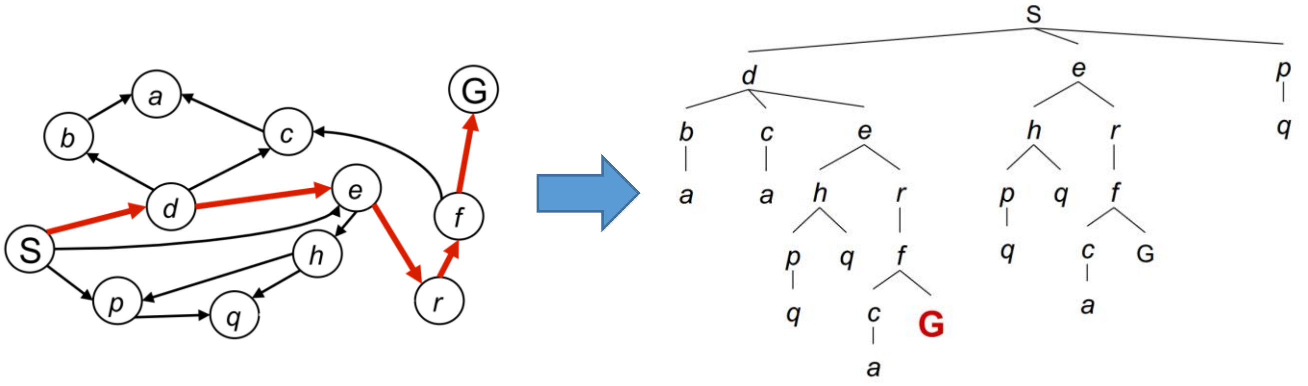
Grid-based graph: use grid as vertices and grid connections as edges



The graph generated by probabilistic roadmap (PRM)

Graph Search Overview

- The search always start from start state X_S
  - Searching the graph produces a search tree
  - Back-tracing a node in the search tree gives us a path from the start state to that node
  - For many problems we can never actually build the whole tree, too large or inefficient – we only want to reach the goal node asap.



Graph Search Overview

- Maintain a container to store all the nodes to be visited
- The container is initialized with the start state X_S
- Loop
  - Remove a node from the container according to some pre-defined score function
    - Visit a node
  - Expansion: Obtain all neighbors of the node
    - Discover all its neighbors
  - Push them (neighbors) into the container
- End Loop

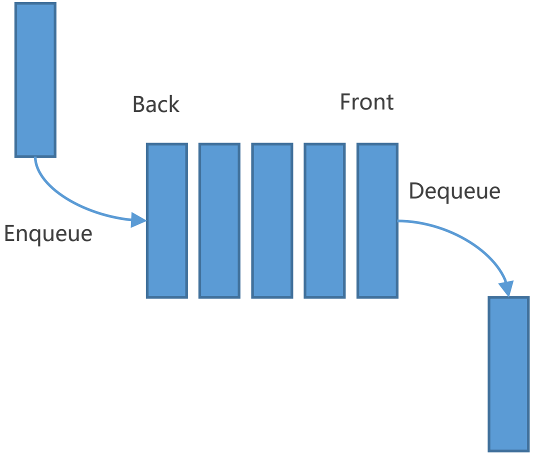
Graph Search Overview

- Question 1: When to end the loop?
  - Possible option: End the loop when the container is empty
- Question 2: What if the graph is cyclic?
  - When a node is removed from the container (expanded / visited), it should never be added back to the container again
- Question 3: In what way to remove the right node such that the goal state can be reached as soon as possible, which results in less expansion of the graph node.

Graph Traversal

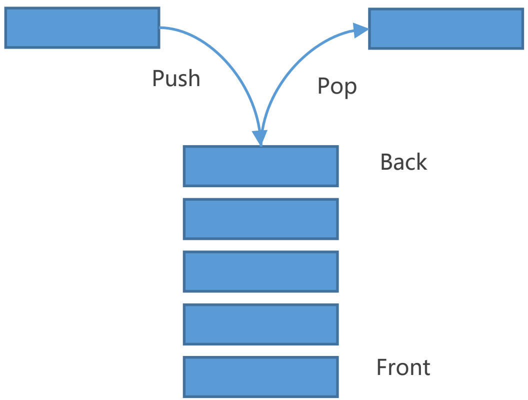
- Breadth First Search (BFS) vs. Depth First Search (DFS)

BFS uses "first in first out"



This is a queue

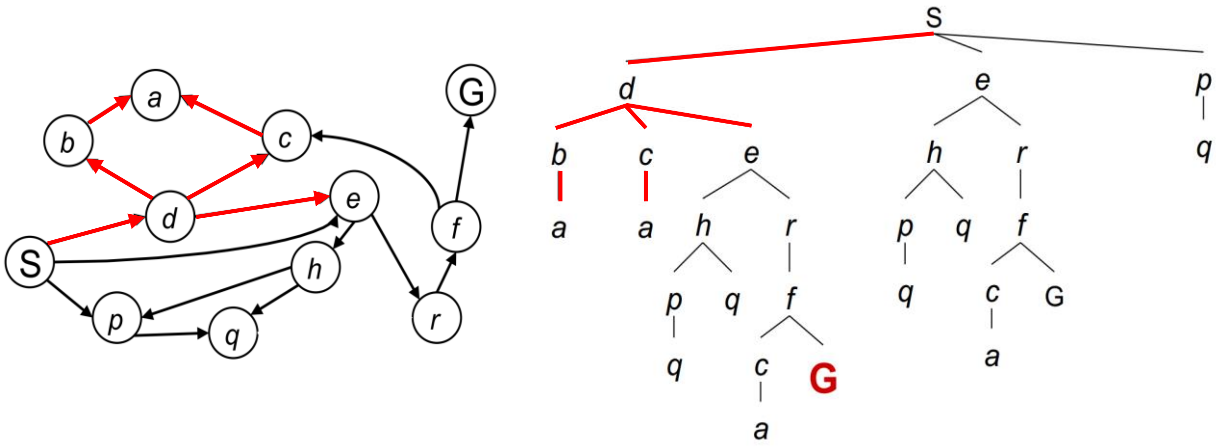
DFS uses "last in first out"



This is a stack

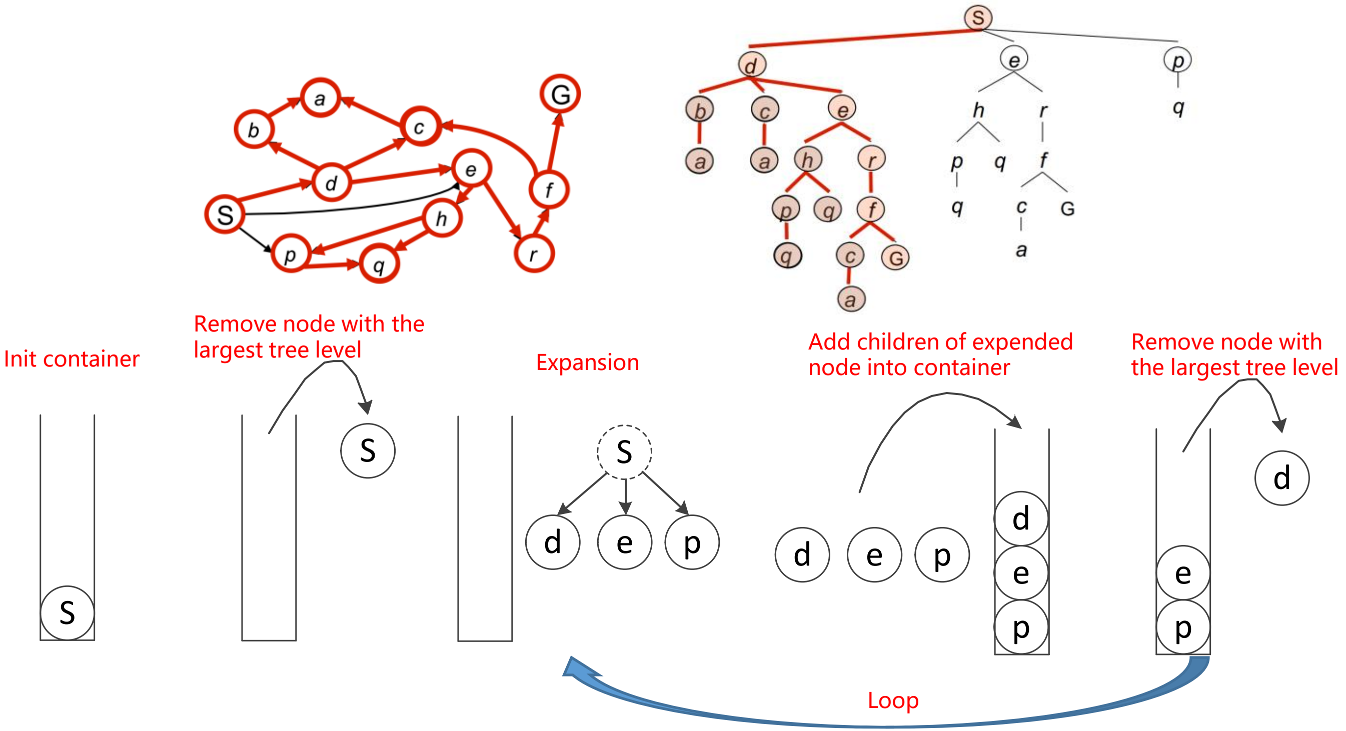
Depth First Search (DFS)

- Strategy: remove / expand the deepest node in the container

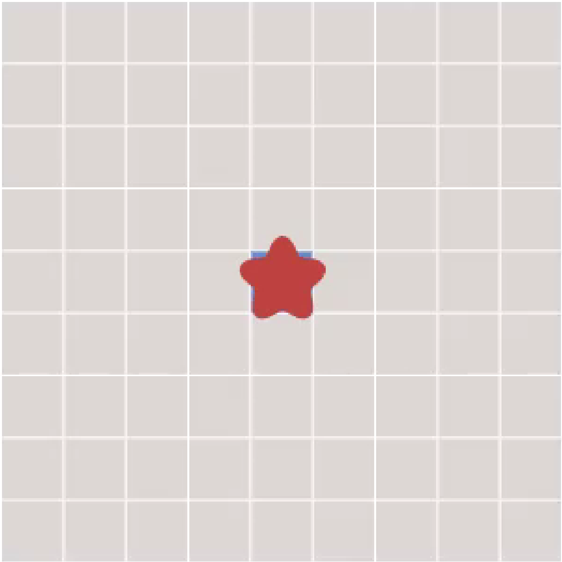


Depth First Search (DFS)

- Implementation: maintain a last in first out (LIFO) container (i.e. stack)



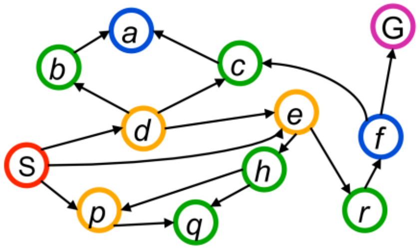
Depth First Search (DFS)

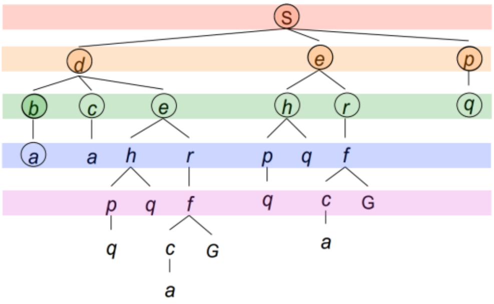


Courtesy: Amit Patel's Introduction to A*, Stanford

Breadth First Search (BFS)

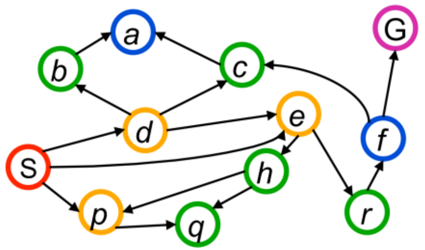
- Strategy: remove / expand the shallowest node in the container

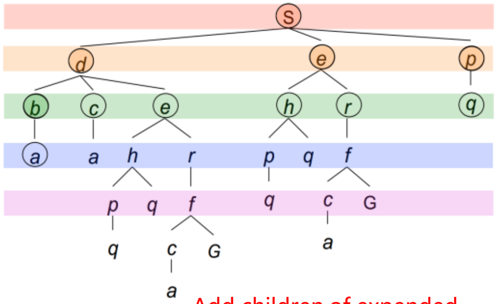


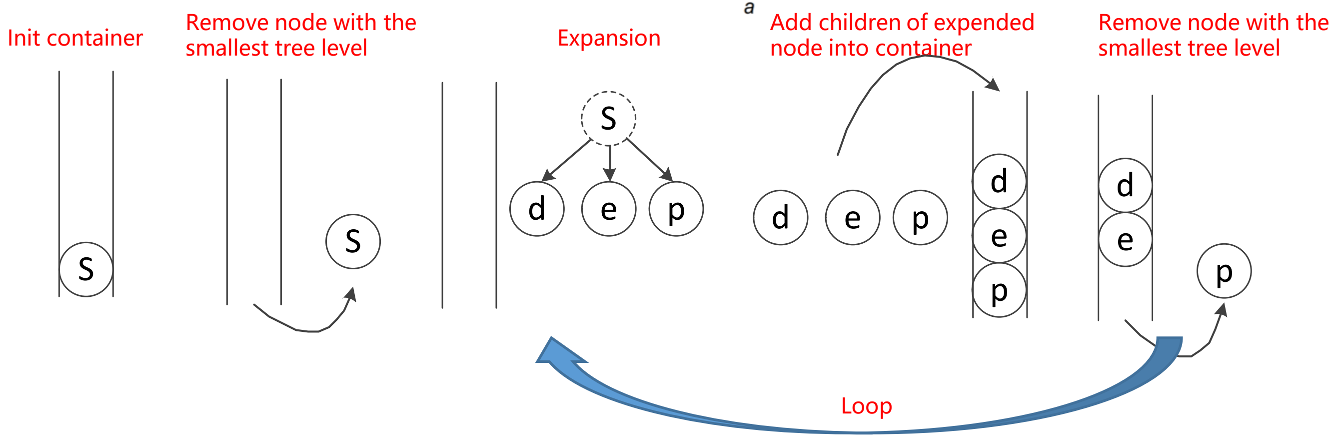


Breadth First Search (BFS)

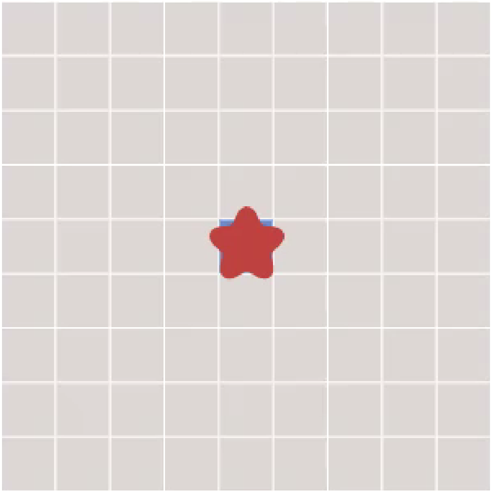
- Implementation: maintain a first in first out (FIFO) container (i.e. queue)





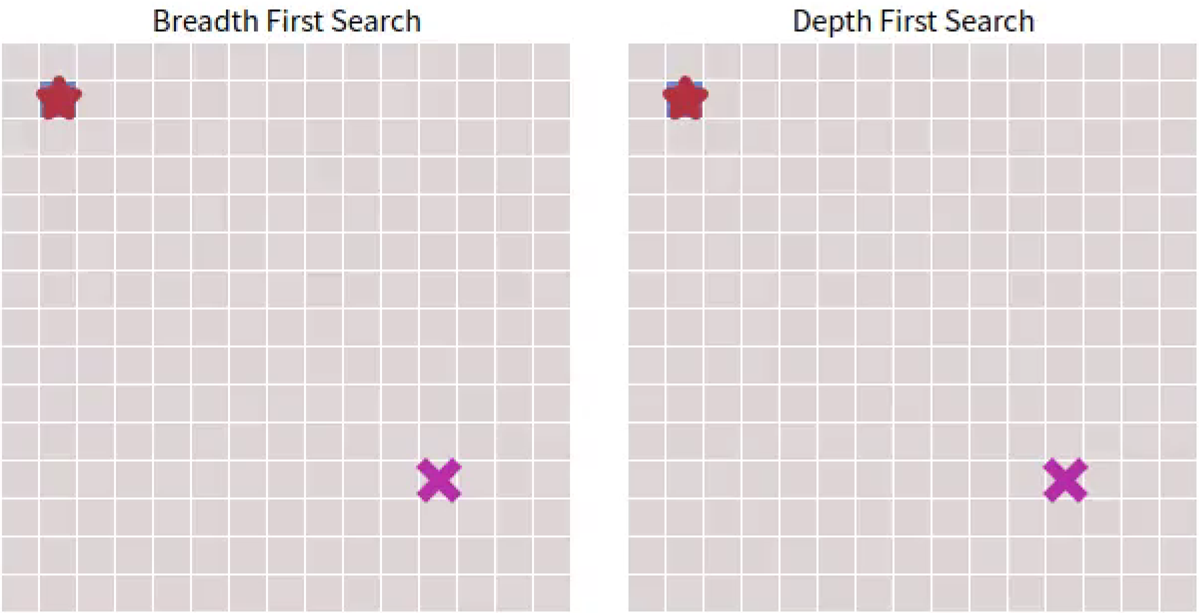


Breadth First Search (BFS)



Courtesy: Amit Patel's Introduction to A*, Stanford

BFS vs. DFS: which one is useful?



Remember BFS.

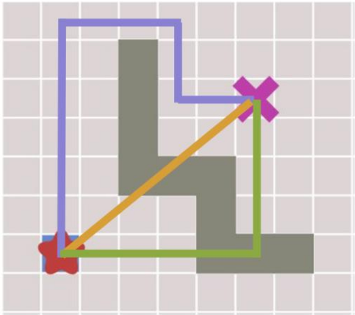
Heuristic search

Greedy Best First Search

- BFS and DFS pick the next node off the frontiers based on which was “first in” or “last in”.
- Greedy Best First picks the “best” node according to some rule, called a heuristic.

- Definition: A heuristic is a guess of how close you are to the target.

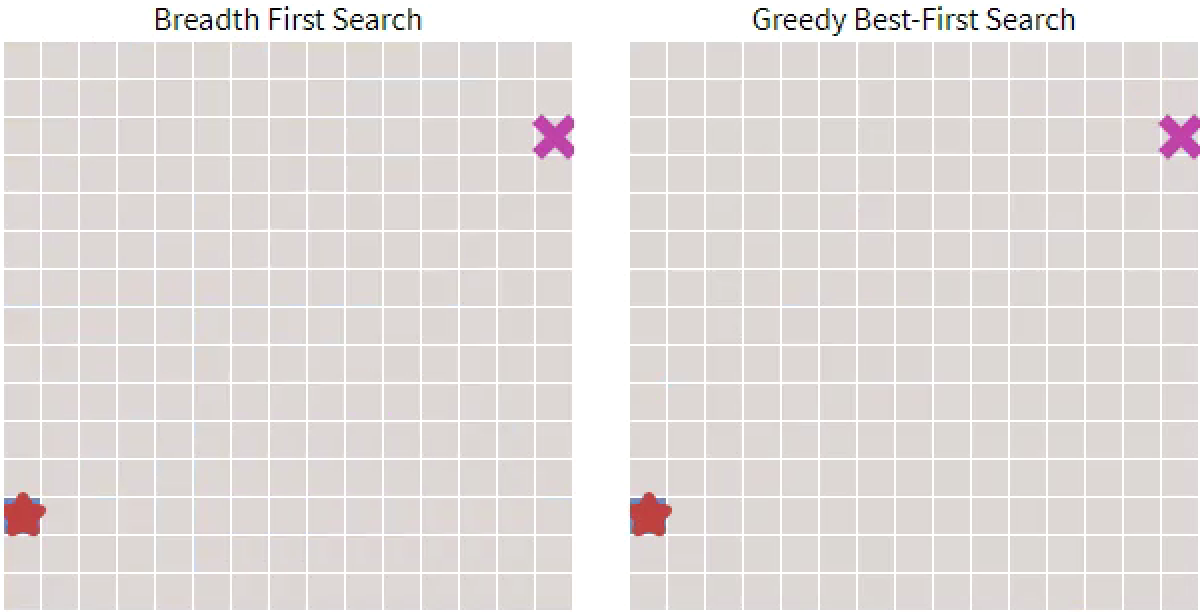
- A heuristic guides you in the right direction.
- A heuristic should be easy to compute.



- Euclidean Distance
- Manhattan Distance

Both are approximations for the actual shortest path.

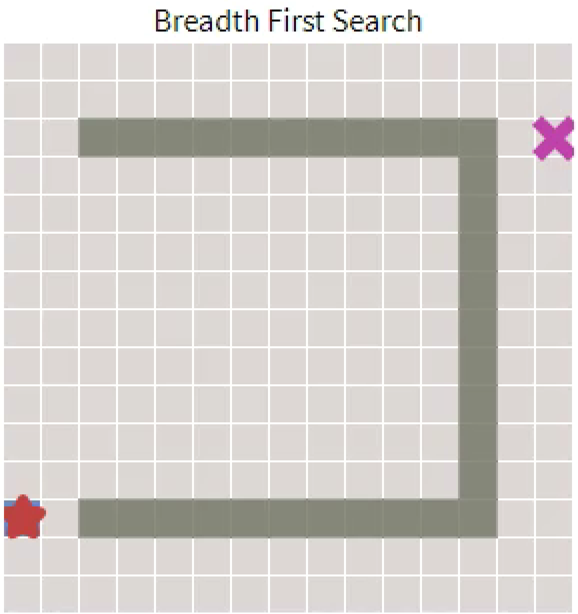
Greedy Best First Search

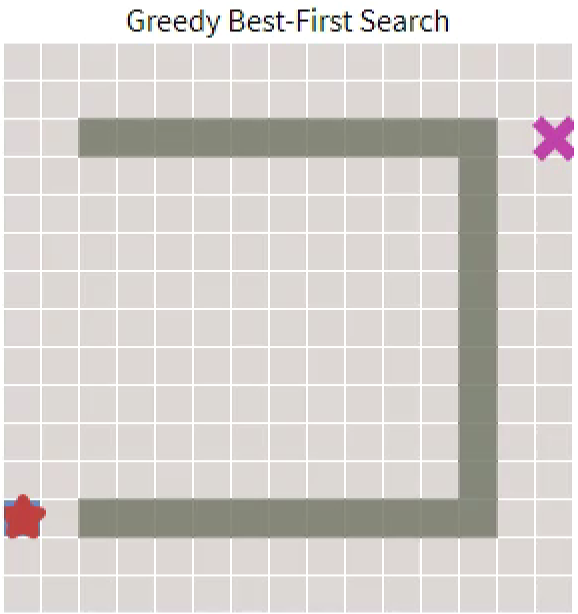


Looks pretty good.

Courtesy: Amit Patel's Introduction to A*, Stanford

Greedy Best First Search



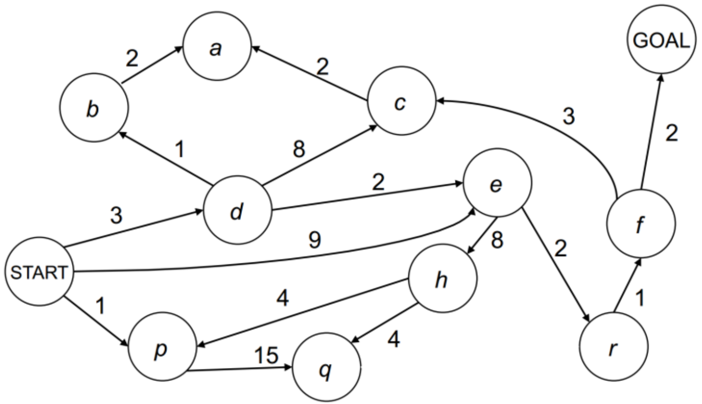


But with obstacles …

Courtesy: Amit Patel's Introduction to A*, Stanford

Costs on Actions

- A practical search problem has a cost "C" from a node to its neighbor
  - Length, time, energy, etc.
- When all weight are 1, BFS finds the optimal solution
- For general cases, how to find the least-cost path as soon as possible?

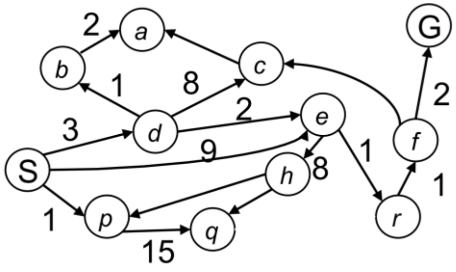


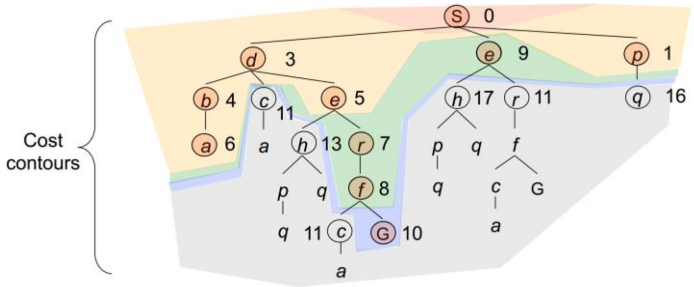
Dijkstra and A*

Algorithm Workflow

Dijkstra’s Algorithm

- Strategy: expand/visit the node with cheapest accumulated cost g(n)
  - g(n): The current best estimates of the accumulated cost from the start state to node “n”
  - Update the accumulated costs g(m) for all unexpanded neighbors “m” of node “n”
  - A node that has been expanded/visited is guaranteed to have the smallest cost from the start state

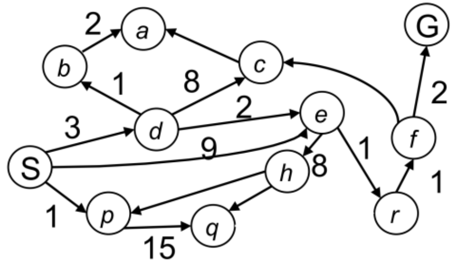


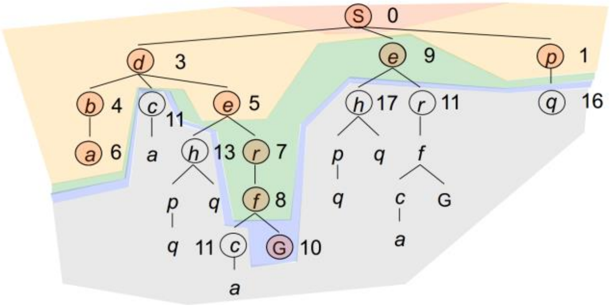


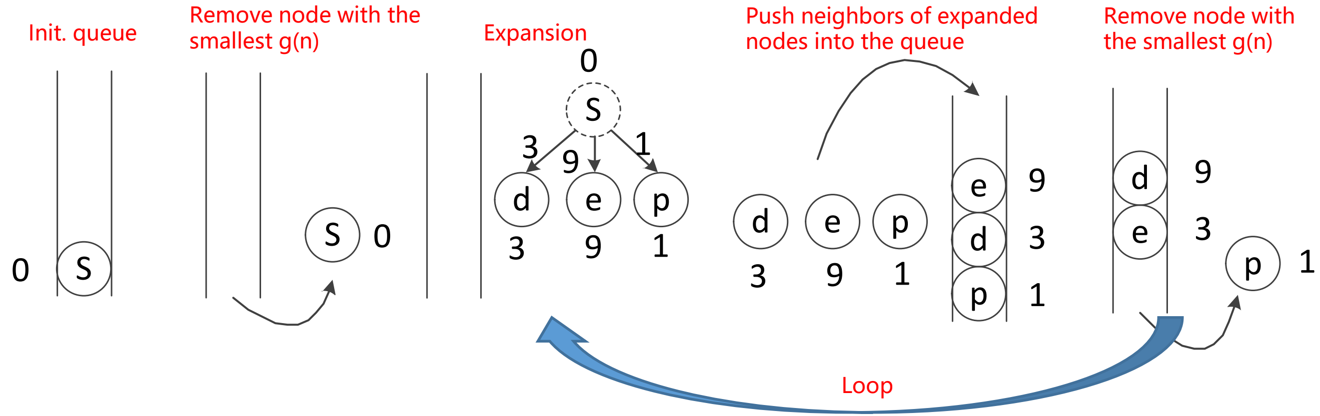
Dijkstra's Algorithm

- Maintain a priority queue to store all the nodes to be expanded
- The priority queue is initialized with the start state X_S
- Assign $g(X_S)=0$, and $g(n)$=infinite for all other nodes in the graph
- Loop
  - If the queue is empty, return FALSE; break;
  - Remove the node "n" with the lowest g(n) from the priority queue
  - Mark node "n" as expanded
  - If the node "n" is the goal state, return TRUE; break;
  - For all unexpanded neighbors "m" of node "n"
    - If g(m) = infinite
      - g(m)= g(n) + Cnm
      - Push node "m" into the queue
    - If $g(m) > g(n) + C_{nm}$
      - $g(m)= g(n) + C_{nm}$
  - end
- End Loop

Dijkstra’s Algorithm

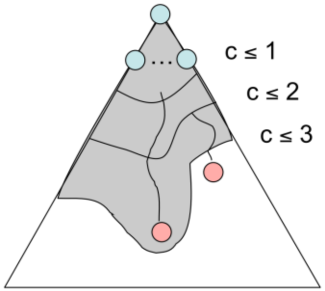


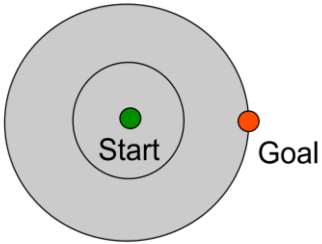




Pros and Cons of Dijkstra’s Algorithm

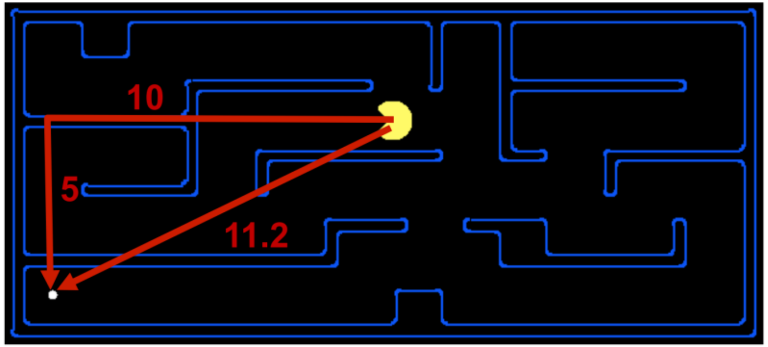
- The good:
  - Complete and optimal
- The bad:
  - Can only see the cost accumulated so far (i.e. the uniform cost), thus exploring next state in every “direction”
  - No information about goal location





Search Heuristics

- Recall the heuristic introduced in **Greedy Best First Search**
- Overcome the shortcomings of uniform cost search by inferring the least cost to goal (i.e. goal cost)
- Designed for particular search problem
- Examples: Manhattan distance VS. Euclidean distance



A*: Dijkstra with a Heuristic

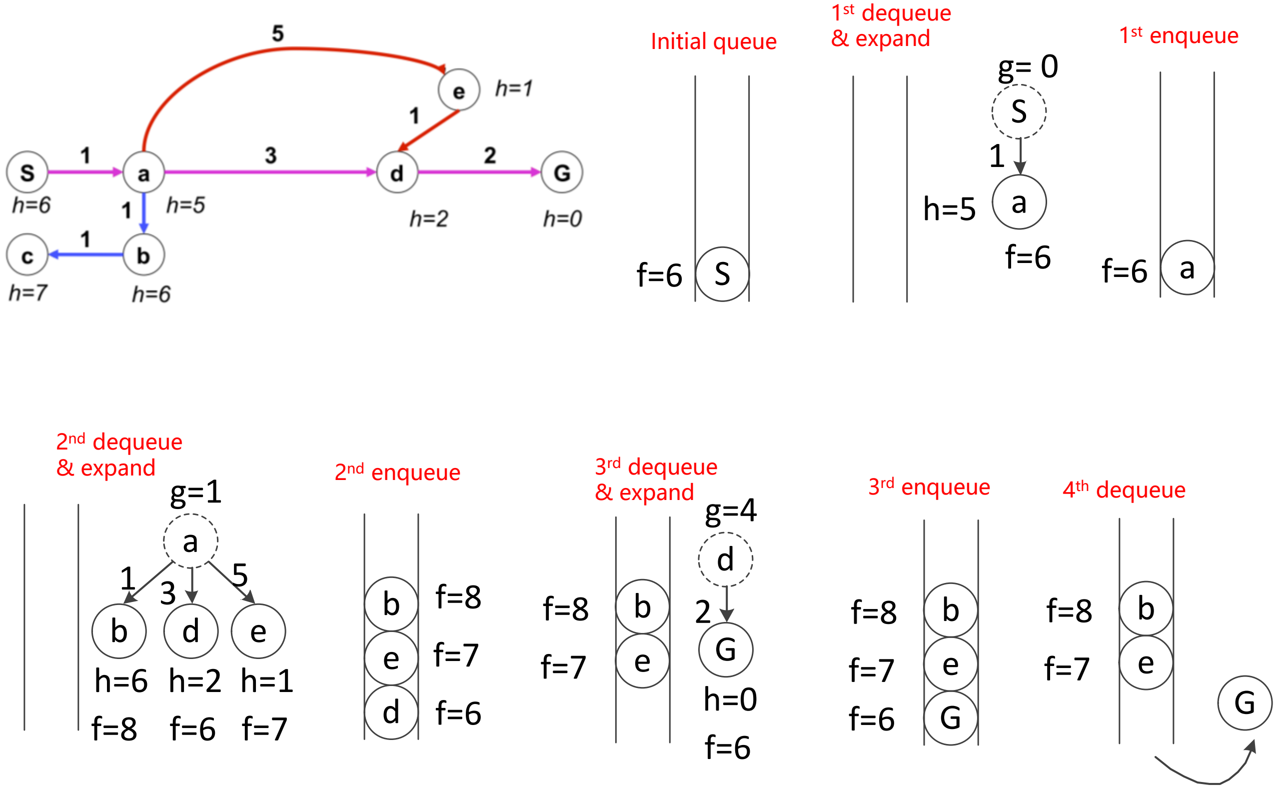
- Accumulated cost
  - g(n): The current best estimates of the accumulated cost from the start state to node “n”
- Heuristic
  - h(n): The **estimated least cost** from node n to goal state (i.e. goal cost)
- The least estimated cost from start state to goal state passing through node “n” is f(n) = g(n) + h(n)
- Strategy: expand the node with cheapest f(n) = g(n) + h(n)
  - Update the accumulated costs g(m) for all unexpanded neighbors “m” of node “n”
  - A node that has been expanded is guaranteed to have the smallest cost from the start state

A* Algorithm

- Maintain a priority queue to store all the nodes to be expanded
- The heuristic function h(n) for all nodes are pre-defined
- The priority queue is initialized with the start state X_S
- Assign $g(X_S)=0$, and $g(n)$=infinite for all other nodes in the graph
- Loop
  - If the queue is empty, return FALSE; break;
  - Remove the node "n" with the lowest $f(n)=g(n)+h(n)$ from the priority queue
  - Mark node "n" as expanded
  - If the node "n" is the goal state, return TRUE; break;
  - For all unexpanded neighbors "m" of node "n"
    - If g(m) = infinite
      - g(m)= g(n) + Cnm
      - Push node "m" into the queue
    - If $g(m) > g(n) + C_{nm}$
      - g(m)= g(n) + Cnm
  - end
- End Loop

Only difference comparing to Dijkstra's algorithm

A* Example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e
h=1
1
S
1
a
3
d
2
G
h=6
1
h=5
h=2
h=0
c
1
b
h=7
h=6
Initial queue
f=6
S
1st dequeue
& expand
g= 0
S
1
h=5
a
f=6
1st enqueue
f=6
a
2nd dequeue
& expand
g=1
a
1
3
5
b
d
e
h=6
h=2
h=1
f=8
f=6
f=7
2nd enqueue
b
f=8
e
f=7
d
f=6
3rd dequeue
& expand
g=4
f=8
b
d
2
f=7
e
G
h=0
f=6
3rd enqueue
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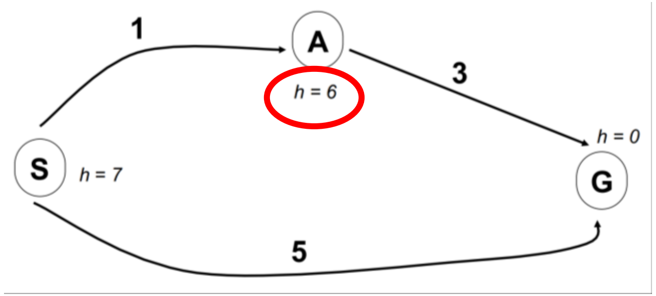
G

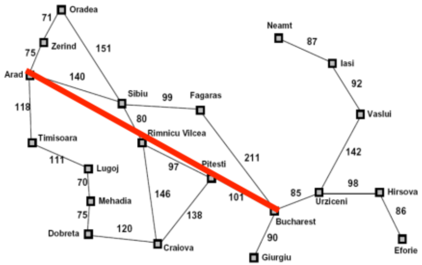
A* Optimality

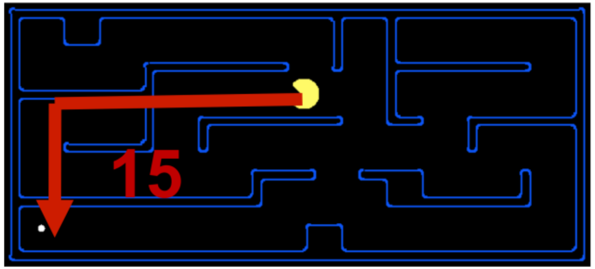


- What went wrong?
- For node A: actual least cost to goal (i.e. goal cost) < estimated least cost to goal (i.e. heuristic)
- We need the estimate to be less than actual least cost to goal (i.e. goal cost) for all nodes!

Admissible Heuristics

- A Heuristic h is admissible (optimistic) if:
  - h(n) <= h*(n) for all node "n", where h*(n) is the true least cost to goal from node "n"
- If the heuristic is admissible, the A* search is optimal
- Coming up with admissible heuristics is most of what's involved in using A* in practice.
- Example:

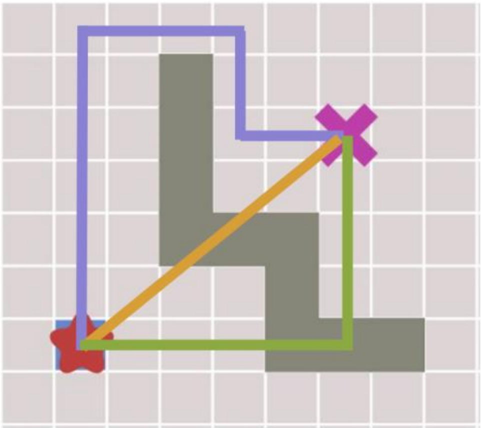




Heuristic Design

An admissible heuristic function has to be designed case by case.

- Euclidean Distance
- Manhattan Distance



Is Euclidean distance (L2 norm) admissible? Always

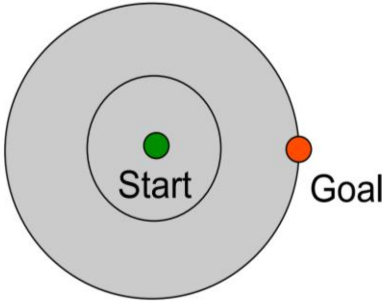
Is Manhattan distance (L1 norm) admissible? Depends

Is $L\infty$ norm distance admissible? Always

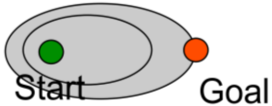
Is 0 distance admissible? Always

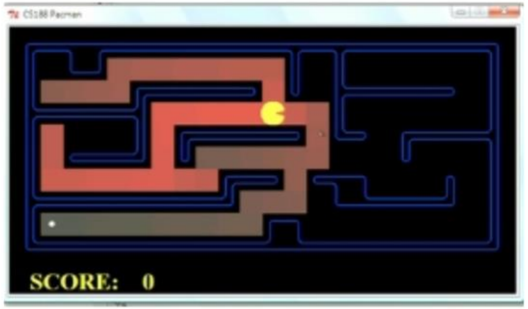
Dijkstra’s VS A*

- Dijkstra’s algorithm expanded in all directions



- A* expands mainly towards the goal, but does not hedge its bets to ensure optimality



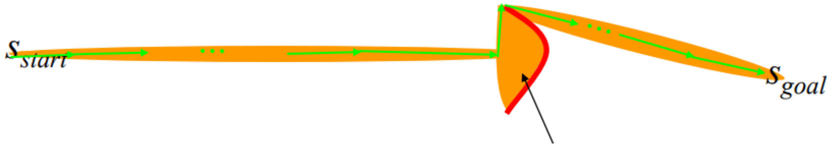


Sub-optimal Solution

What if we intend to use an over-estimate heuristic?

- Suboptimal path
- Faster

Weighted A*: Expands states based on $f = g + \varepsilon h, \varepsilon > 1$ =bias towards states that are closer to goal.



Shallow local minima

- Weighted A* Search:

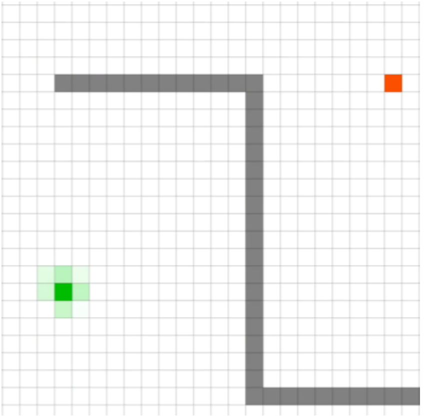
➢ Optimality vs. speed
➢ ε-suboptimal:
cost(solution) <= εcost (optimal solution)
➢ It can be orders of magnitude faster than A*

Weighted A*-> Anytime A*-> ARA*->D*

Beyond the scope of this course

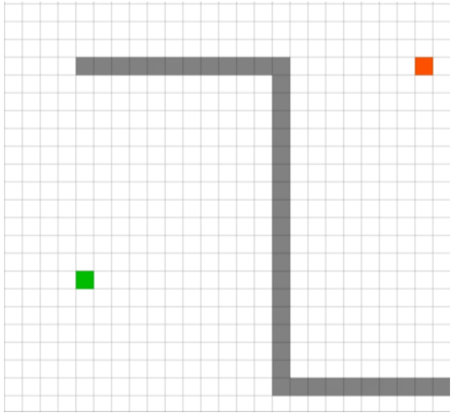
Greedy Best First Search vs. Weighted A* vs. A*

$$f = a \cdot g + b \cdot h$$



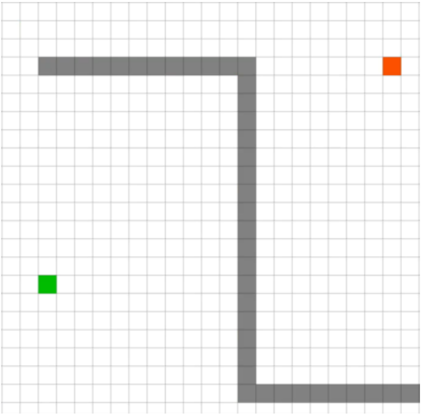
Most Greedy

$$a = 0, b = 1$$



Tunable Greediness

$$a = 1, b = \varepsilon > 1$$



Optimal

$$a = 1, b = 1$$

Dijkstra: $a = 1, b = 0$

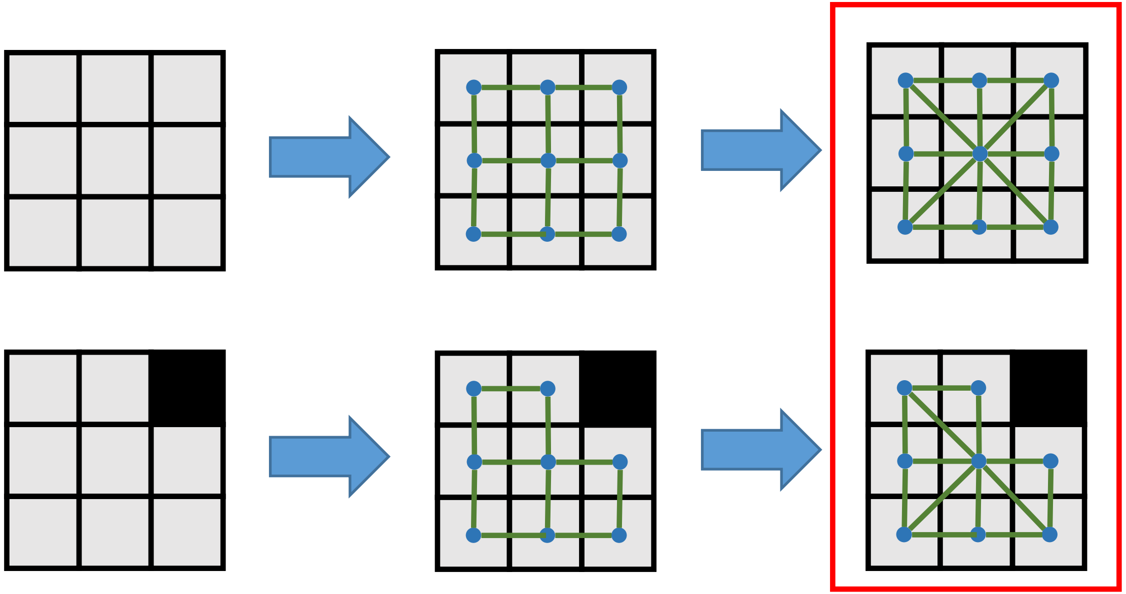
Animation from: http://qiao.github.io/PathFinding.js/visual/

Engineering Considerations

Example： Grid-based Path Search

How to represent grids as graphs?

Each cell is a node. Edges connect adjacent cells.

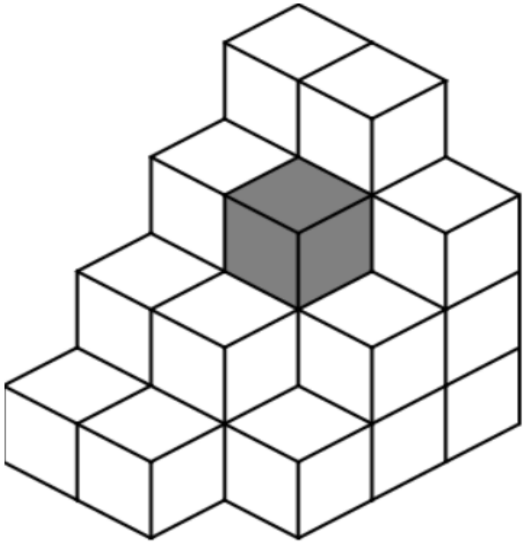


Common Choice!

4 connection

8 connection

Grid-based Path Search: Implementation



- Create a dense graph.
- Link the occupancy status stored in the grid map.
- Neighbors discovered by grid index.
- Perform A* search.

- Priority queue in C++
  - std::priority_queue
  - std::make_heap
  - std::multimap

The Best Heuristic

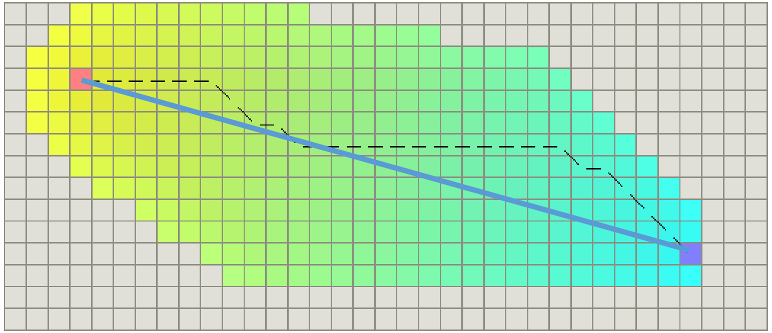
- Recall:
  - Is Euclidean distance (L2 norm) admissible? ✓
  - Is Manhattan distance (L1 norm) admissible? ✗
  - Is L∞ norm distance admissible? ✓
  - Is 0 distance admissible? ✓

They are useful, but none of them is the best choice, why?

Because none of them is tight.

Tight means who close they measure the true shortest distance.

Euclidean Heuristic



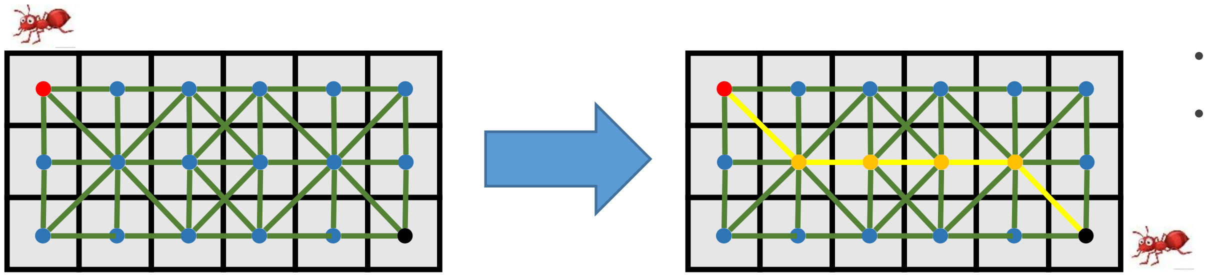
Why so many nodes expanded?

Because Euclidean distance is far from the truly theoretical optimal solution.

The Best Heuristic

How to get the truly theoretical optimal solution?

Fortunately, the grid map is highly structural.



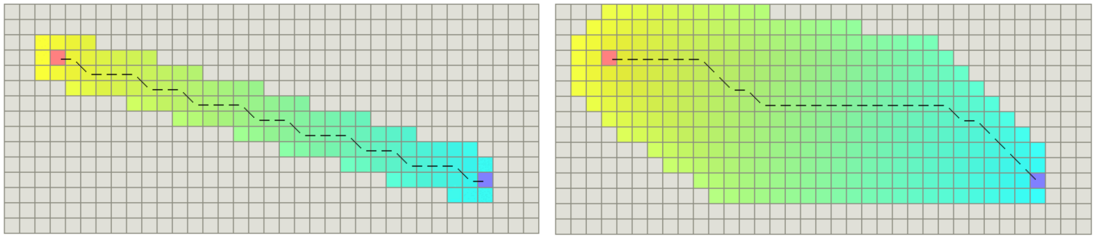
- You don’ t need to search the path.
- It has the closed-form solution!

dx=abs(node.x −goal.x)
dy=abs(node.y −goal.y)
$h=(dx+dy)+(\sqrt{2}-2)*\min(dx,dy)$

For 3D case, we also have a similar version of this.

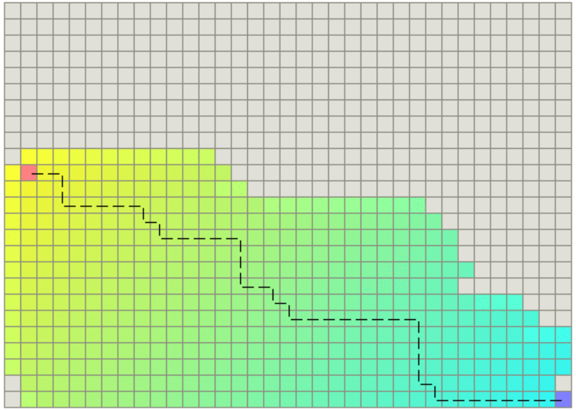
Compare

Diagonal Heuristic



Tie Breaker

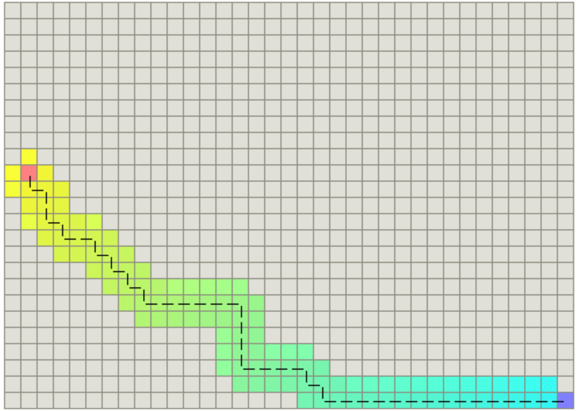
- Many paths have the same f value.
- No differences among them making them explored by A* equally.



- Manipulate the f value breaks the tie.
- Make same f values differ.
- Interfere h slightly.

$$\mathrm{h} = \mathrm{h} \times (1.0 + \mathrm{p})$$

$$p < \frac{minimum\ cost\ of\ one\ step}{expected\ maximum\ path\ cost}$$



Slightly breaks the admissibility of h, does it matter?

Tie Breaker

Core idea of tie breaker:

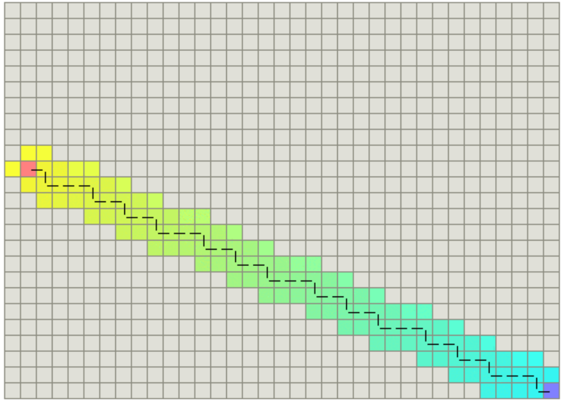
Find a preference among same cost paths

- When nodes having same f, compare their h.
- Add deterministic random numbers to the heuristic or edge costs (A hash of the coordinates).
- Prefer paths that are along the straight line from the starting point to the goal.

$$dx1 = abs(node.x - goal.x)$$
$$dy1 = abs(node.y - goal.y)$$
$$dx2 = abs(start.x - goal.x)$$
$$dy2 = abs(start.y - goal.y)$$
$$cross = abs(dx1 \times dy2 - dx2 \times dy1)$$
$$\mathrm{h} = h + cross \times 0.001$$

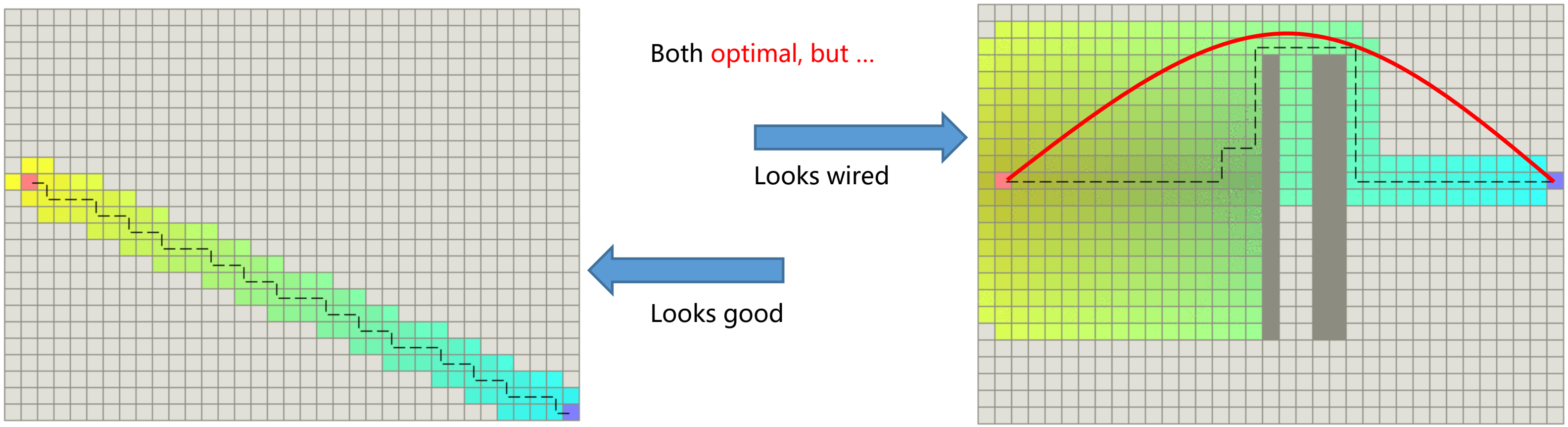
- … Many customized ways

Better/other tie breaker?



Tie Breaker

- Prefer paths that are along the straight line from the starting point to the goal.



It’s the shortest path, but harm for trajectory generation (smoothing).

Or a systematic approach: Jump Point Search (JPS)

Jump Point Search

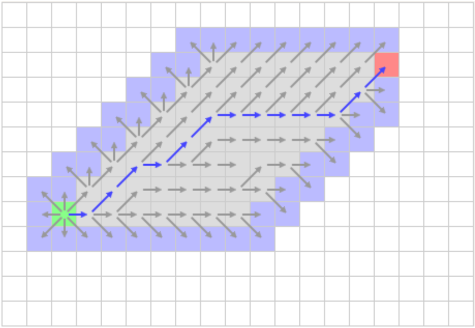
Algorithm Workflow

Jump Point Search

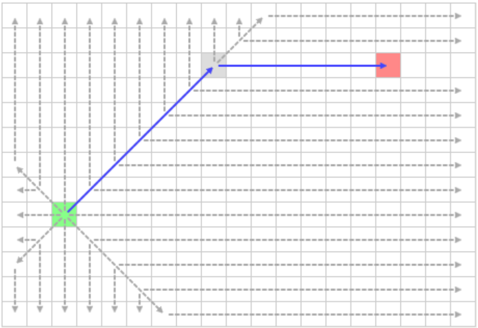
Core idea of JPS:

Find symmetry and break them.

A* explore all symmetric path.



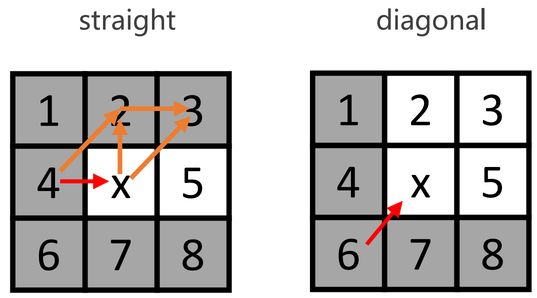
JPS choose one path.



Grey node: Added in the Open List.

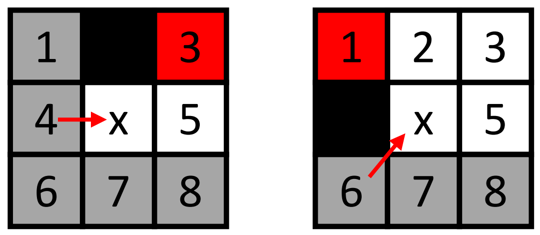
JPS explores intelligently, because it always looks ahead based on a rule.

Look Ahead Rule



Consider:

- current node x
- x's expanded direction



Neighbor Pruning

- Gray nodes: inferior neighbors, when going to them, the path without x is cheaper. Discard.
- White nodes: natural neighbors.
- We only need to consider natural neighbors when expand the search.

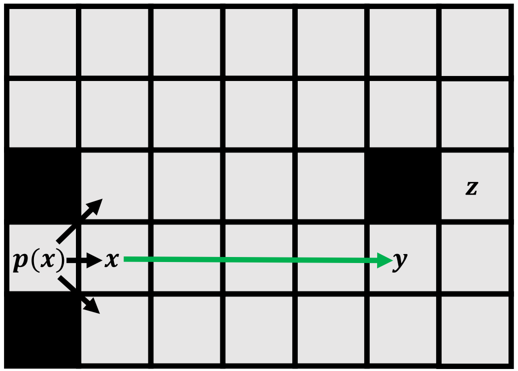
Forced Neighbors

- There is obstacle adjacent to x
- Red nodes are forced neighbors.
- A cheaper path from x's parent to them is blocked by obstacle.

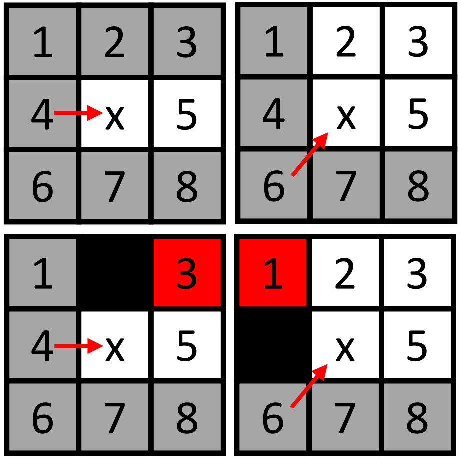
See: http://users.cecs.anu.edu.au/~dharabor/data/papers/harabor-grastien-aaai11.pdf Equation 1/2

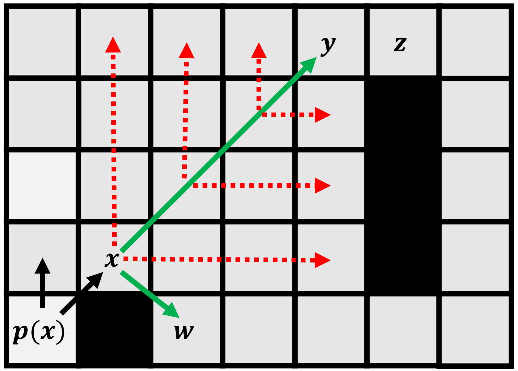
Jumping Rules

Look Ahead Rule



Jumping Straight

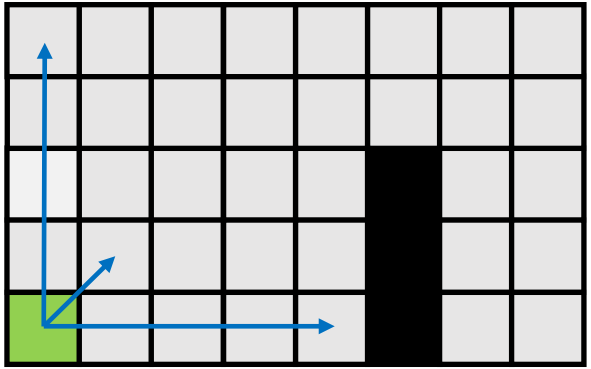




Jumping Diagonally

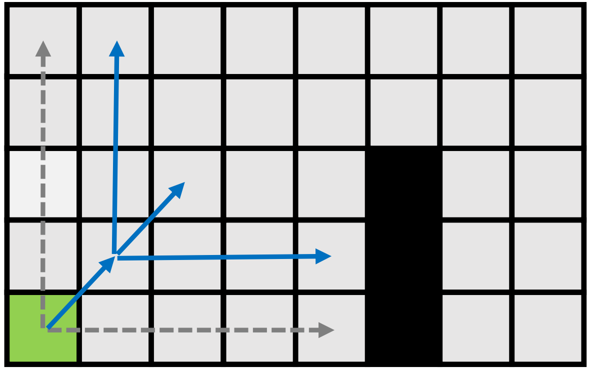
- Recursively apply straight pruning rule and identify y as a jump point successor of x. This node is interesting because it has a neighbor z that cannot be reached optimally except by a path that visits x then y.
- Recursively apply the diagonal pruning rule and identify y as a jump point successor of x.
- Before each diagonal step we first recurse straight. Only if both straight recursions fail to identify a jump point do we step diagonally again.
- Node w, a forced neighbor of x, is expanded as normal. (also push into the open list, the priority queue)

Jump Point Search



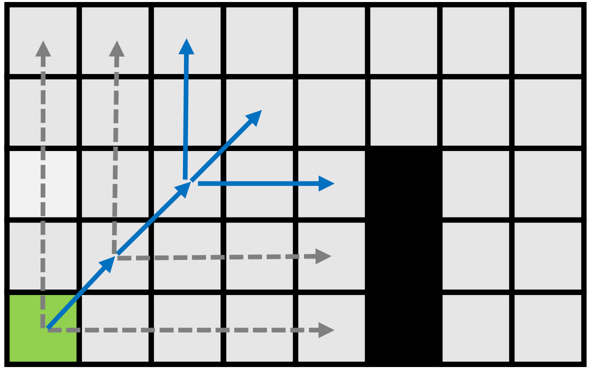
- Expand horizontally and vertically.
- Both jumps end in obstacles.
- Move diagonally.

Jump Point Search



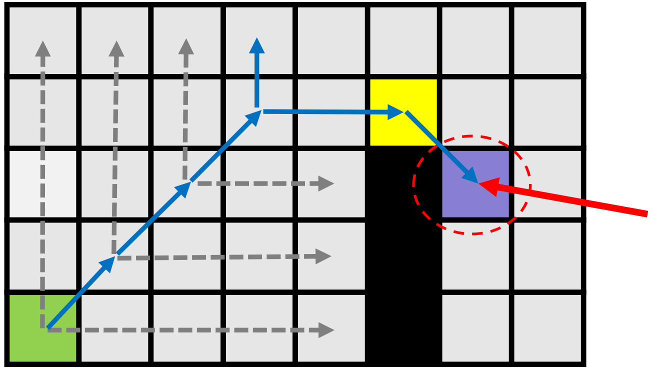
- Expand horizontally and vertically.
- Both jumps end in obstacles.
- Move diagonally.

Jump Point Search



- Expand horizontally and vertically.
- Both expansions end in obstacles.
- Move diagonally.

Jump Point Search

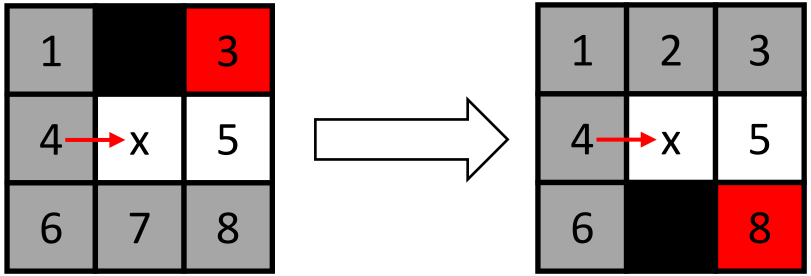


- Remember: you can only jump straight or diagonally; never piecewise jump

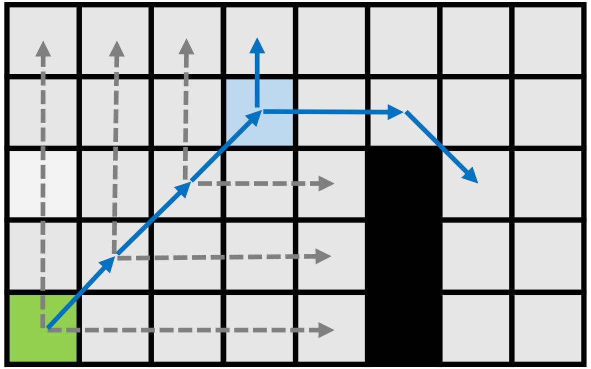
- Vertically expansion end in obstacle.
- Right-ward expansion finds a node with a forced neighbor.

Recall the rule

So we have



Jump Point Search



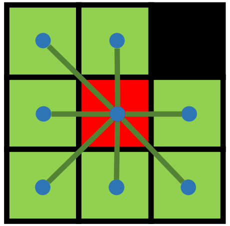
- Now this node is of interested.
- Put it to open list.

Jump Point Search

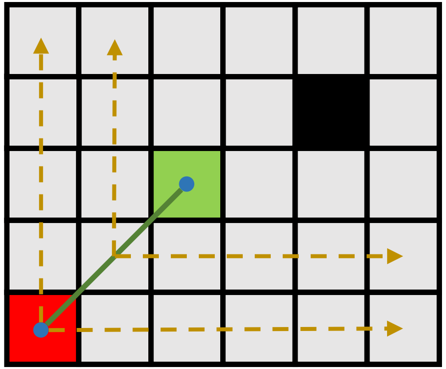
Recall A*'s pseudo-code, JPS's is all the same!

- Maintain a priority queue to store all the nodes to be expanded
- The heuristic function h(n) for all nodes are pre-defined
- The priority queue is initialized with the start state X_S
- Assign $g(X_S)=0$, and g(n)=infinite for all other nodes in the graph
- Loop
  - If the queue is empty, return FALSE; break;
  - Remove the node "n" with the lowest f(n)=g(n)+h(n) from the priority queue
  - Mark node "n" as expanded
  - If the node "n" is the goal state, return TRUE; break;
  - For all unexpanded neighbors "m" of node "n"
    - If g(m) = infinite
      - $g(m)= g(n) + C_{nm}$
      - Push node "m" into the queue
    - If $g(m) > g(n) + C_{nm}$
      - $g(m)= g(n) + C_{nm}$
  - end
- End Loop

A*: "Geometric" neighbors



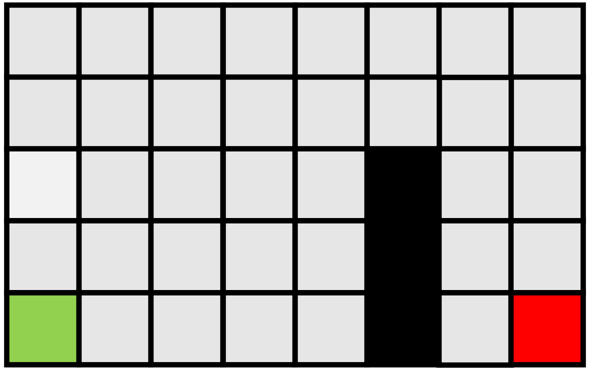
JPS: "Jumping" neighbors



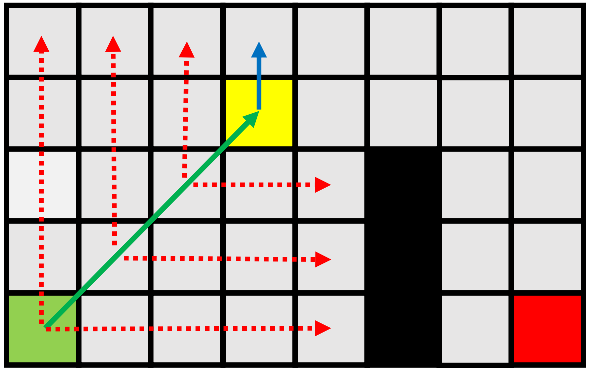
Example

Jumping Example

Planning Case

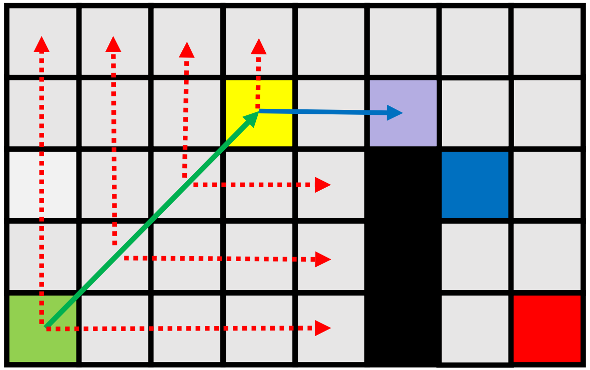


Jumping Example



- Expand—>move diagonally
- Find a critical node finally, add it into open list.
- Pop it（the only one） from the open list.
- Expand vertically, end at obstacles.

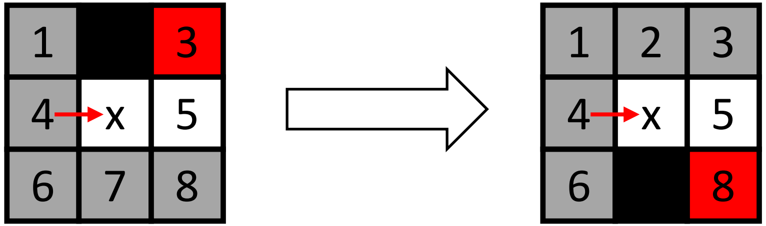
Jumping Example



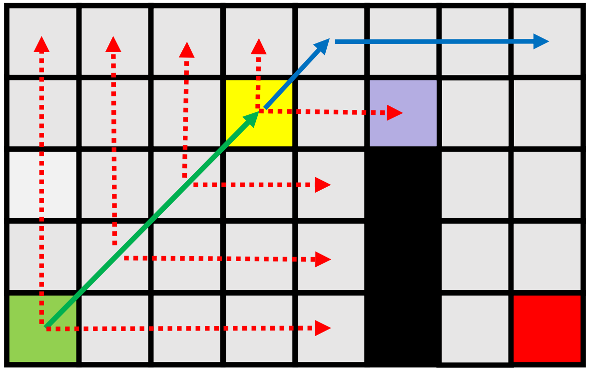
- Expand horizontally, meets a node with a forced neighbor.
- Add it to open list

Recall the rule

So we have

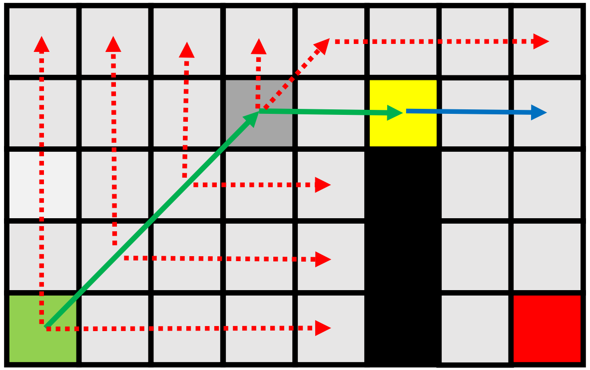


Jumping Example



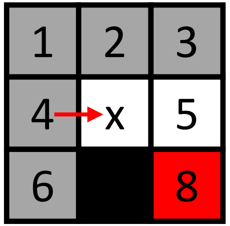
- Expand diagonally, expand, find nothing.
- Finish the expansion of the current node.

Jumping Example

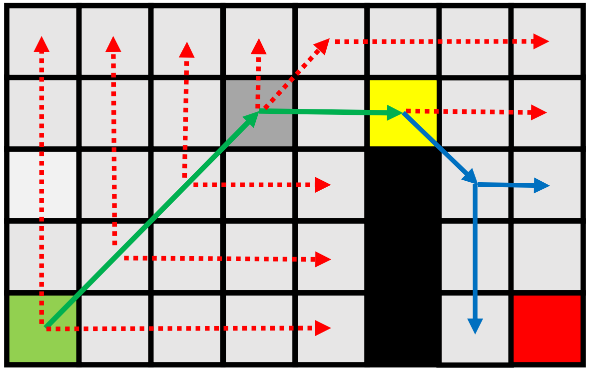


- Examine the “new best” node in the open list.
- Expand horizontally.
- Finds nothing.

Remember the rule

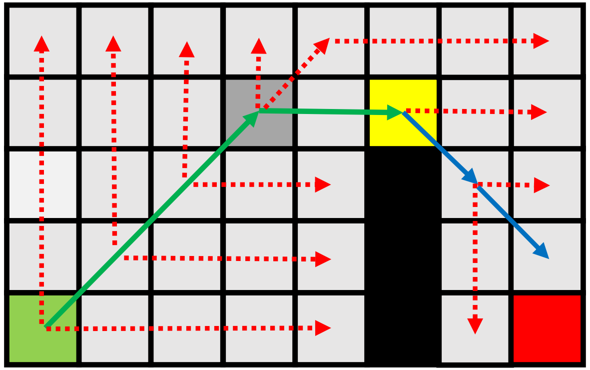


Jumping Example



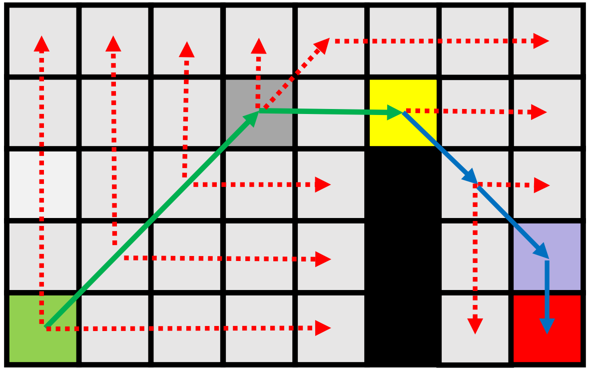
- Move diagonally.
- Expand along vertical and horizontal first.

Jumping Example



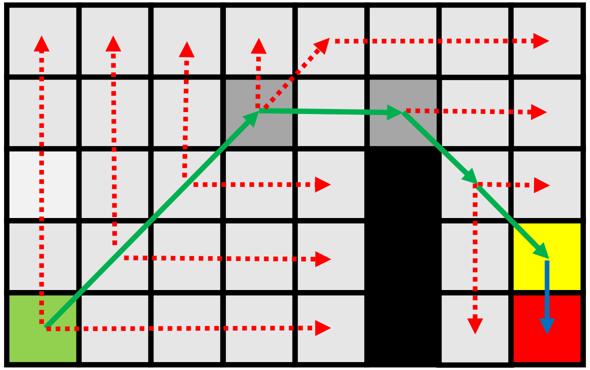
- Finds nothing.
- Move diagonally.

Jumping Example



- Expand horizontally and vertically.
- Finds the goal. Equally interested as finding a node with a forced neighbor.
- Add this node to open list.
- Finish the expand of the current node (No naturally neighbors left).
- Pop it out of the open list.

Jumping Example

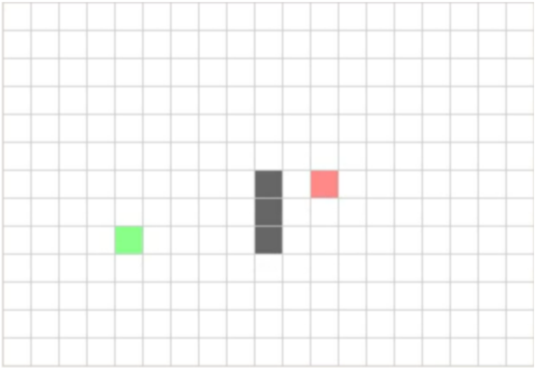


- Examine the “new best” node in the open list.
- Expand horizontally (nowhere), and vertically (finds the goal).
- The end.

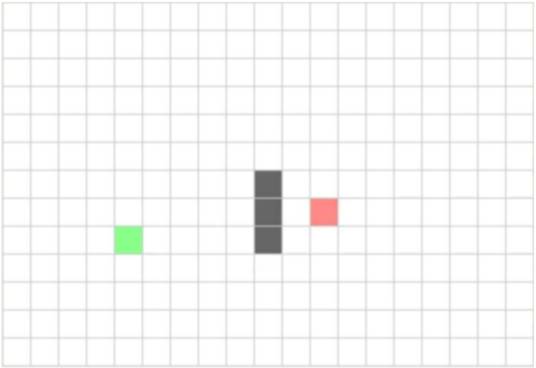
Jumping Example

Final Path

Example



(1)



(2)

Thanks:

https://zerowidth.com/2013/a-visual-explanation-of-jump-point-search.html

Extension

3D JPS

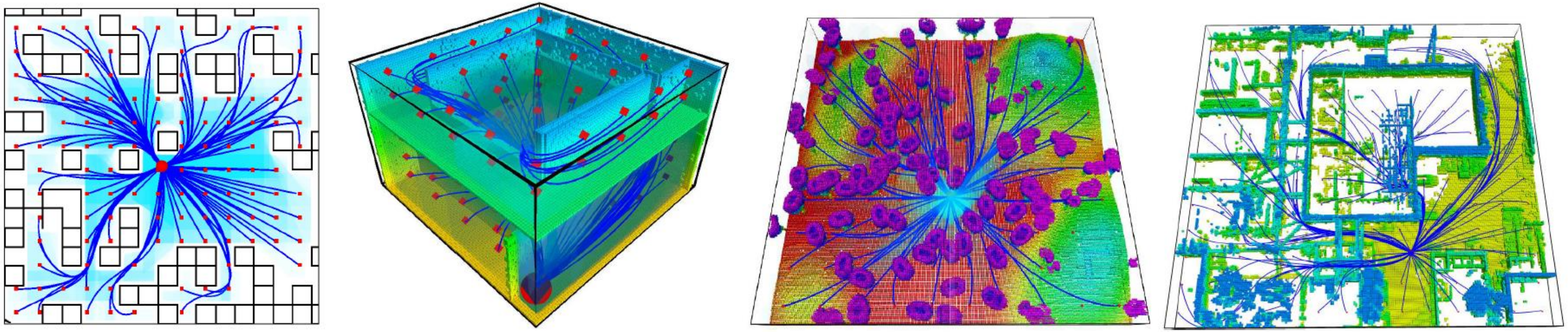


Table 1. Trajectory Generation Run Time (sec)

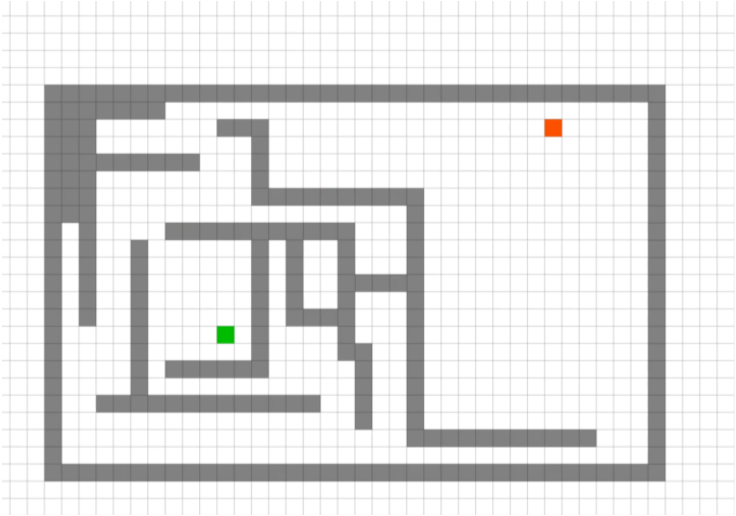
Map	Size	# of Cells	# of Trajs	Time (s)	Path Planning A*	Path Planning JPS	Convex Decomp	Traj Opt	Replan (JPS)
				Avg	0.57	0.034	0.0021	0.028	0.065
Random Blocks	$40 \times 40 \times 1$	1.4×10^6	130	Std	1.26	0.034	0.0028	0.022	0.051
				Max	9.98	0.19	0.020	0.099	0.27
				Avg	6.12	0.039	0.0064	0.082	0.13
Multiple Floors	$10 \times 10 \times 6$	5.9×10^5	147	Std	15.77	0.046	0.0038	0.041	0.081
				Max	84.56	0.22	0.021	0.23	0.45
				Avg	0.65	0.033	0.0039	0.055	0.094
The Forest	$50 \times 50 \times 6$	1.8×10^6	89	Std	1.57	0.044	0.0024	0.031	0.068
				Max	7.78	0.20	0.010	0.12	0.30
				Avg	0.54	0.028	0.0066	0.099	0.14
Outdoor Buildings	$100 \times 110 \times 7$	6.2×10^5	127	Std	1.46	0.045	0.0053	0.064	0.10
				Max	10.96	0.27	0.027	0.24	0.47

Planning Dynamically Feasible Trajectories for Quadrotors using Safe Flight Corridors in 3-D Complex Environments, Sikang Liu, RAL 2017

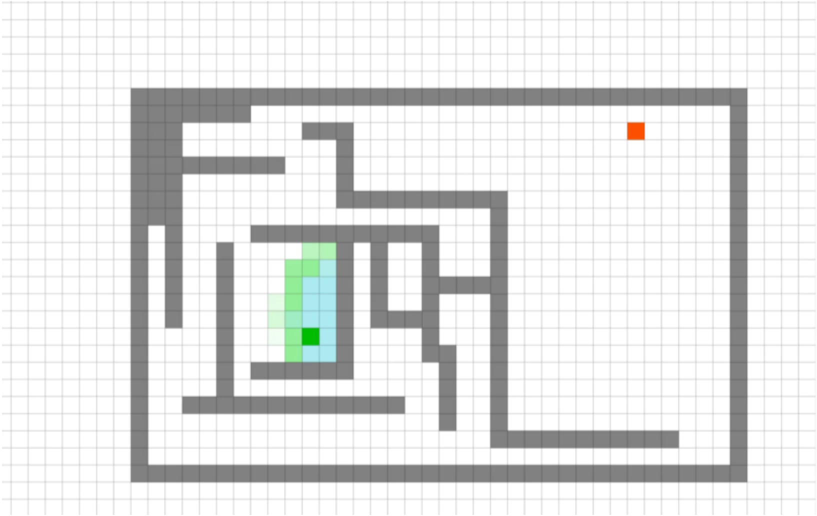
https://github.com/KumarRobotics/jps3d

Is JPS always better?

Maze-like environments



JPS

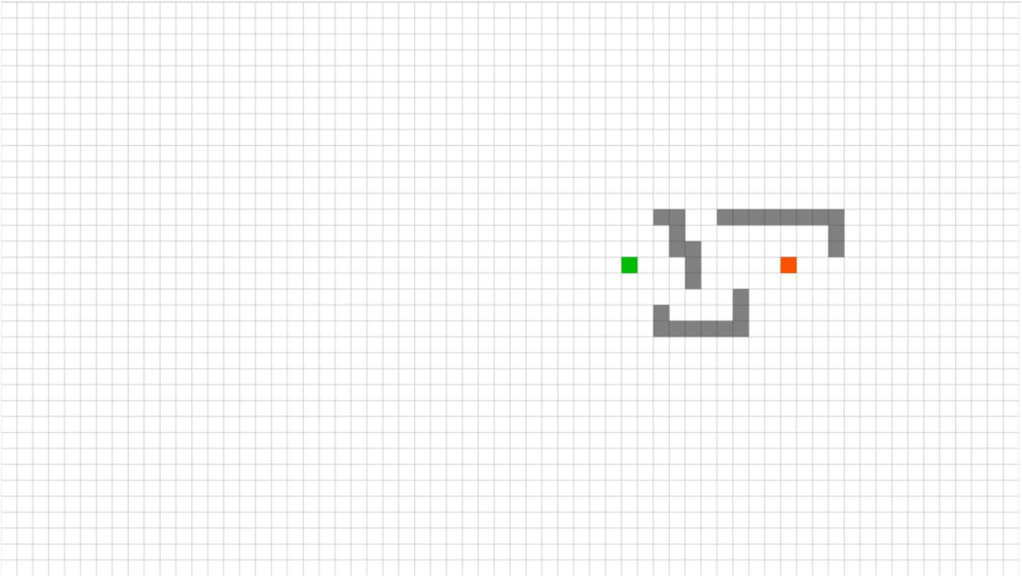


A*

Do more tests by yourself!

Thanks: http://qiao.github.io/PathFinding.js/visual/

Is JPS always better?



- This is a simple example saying “No.”
- This case may commonly occur in robot navigation.
- Robot with limited FOV, but a global map/large local map.

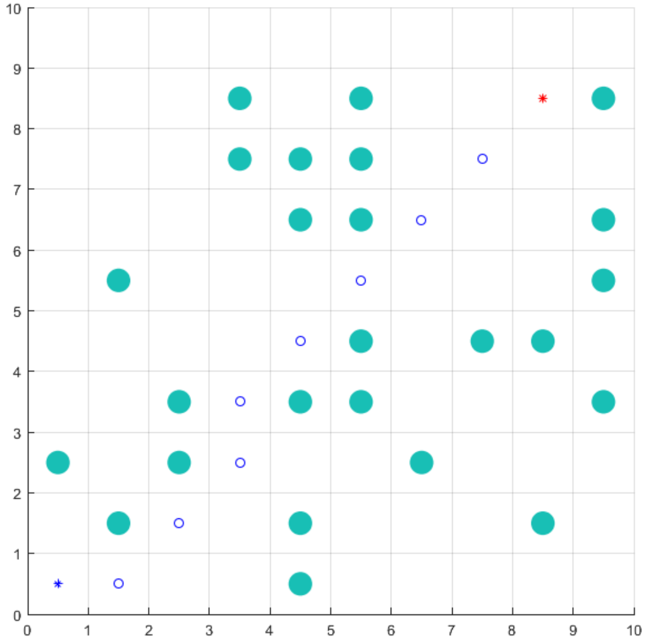
Conclusion:

- Most time, especially in complex environments, JPS is better, but far away from “always”. Why?
- JPS reduces the number of nodes in Open List, but increases the number of status query.
- You can try JPS in Homework 2.
- JPS’s limitation: only applicable to uniform grid map.

Homework

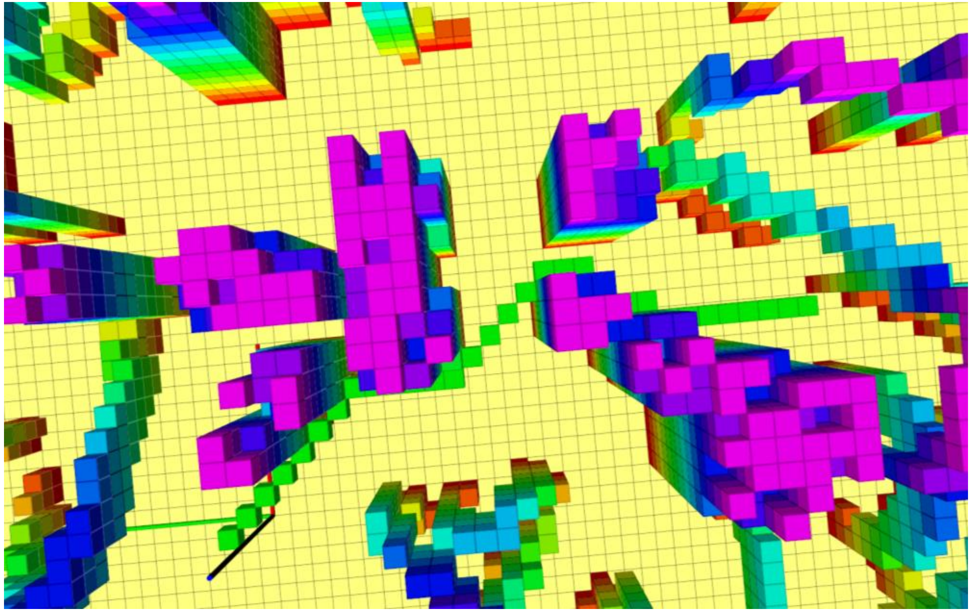
Testing Environment

Matlab



Basic

C++



Advance

Assignment：Basic

- This project work will focus on path Þnding and obstacle avoidance in a 2D grid map.

- A 2D grid map is generated randomly every time the Project is run, which contains the obstacles, start point and target point locations will be provided. You can also change the probability of obstacles in the map in obstacle_map.m

- You need to implement a 2D A* path search method to plan an optimal path with safety guarantee.

Assignment：Advance

- I highly suggest you implement Dijkstra/A* with C++/ROS.
- Complex 3d map can be generated randomly. The sparsity of obstacles in this map is tunable.
- An implementation of JPS is also provided. Comparisons can be made between A* and JPS in different map set-up.

Thanks for Listening!