Chapter 10
Motion Planning

Part 3

10.3 Real Time Global Motion Planning

Outline

- 10.3 Real Time Global Motion Planning
  - 10.3.1 Introduction
  - 10.3.2 Depth Limited Approaches
  - 10.3.3 Anytime Approaches
  - 10.3.4 Plan Repair Approach: D* Algorithm
  - 10.3.5 Hierarchical Planning
  - Summary

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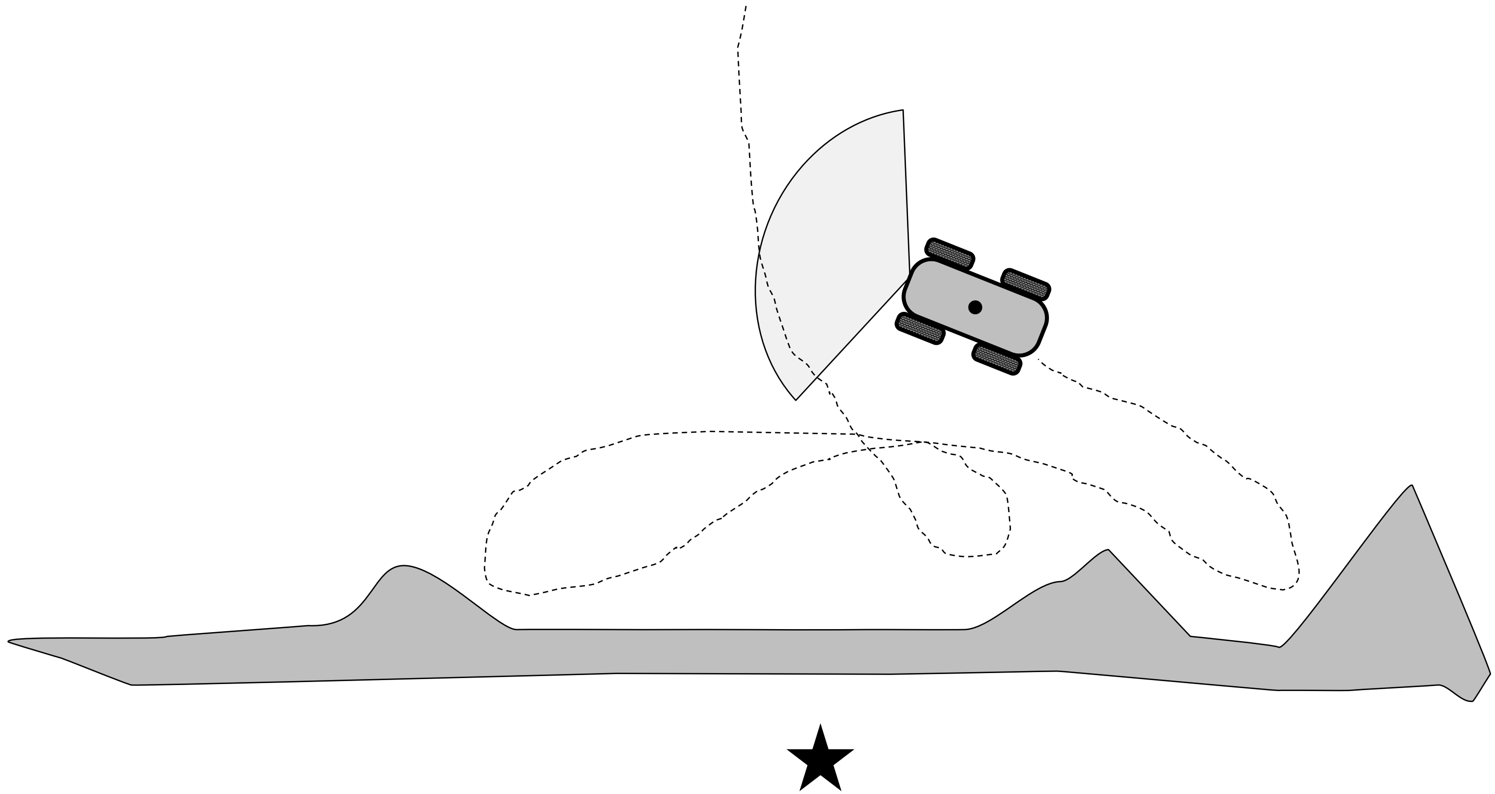
10.3.1 Introduction

- Unknown and dynamic environments can be treated similarly because a dynamic environment is partially unknown.
- Unknown Environments
  - Limited perception limits what you can know.
  - Often, the only way to learn more is to move.
  - You may eventually learn that the path you are on is wrong.
- Dynamic Environments
  - Limited prediction fidelity limits what you can know.
  - Often, the only way to learn more is to wait.

10.3.1 Introduction
(Thinking vs Doing)

- Often, it is possible to trade off the cost of execution and planning.
  - More planning time makes better use of available information.
  - More motion gathers more information.
- Sometimes its better to stop and think, other times not.

10.3.1.1 Unknown Environments
(Changing Strategy)



- It is not unusual for a robot to continue to change its mind as it learns new information.

10.3.1 Introduction

(Four Techniques)

- Four techniques are available to deal with the real time / limited computation issues:
  1. Limited Horizon
     - Don’t predict too far
  2. Anytime Approaches
     - Always have an answer available
  3. Plan Repair
     - Reuse elements of last plan.
  4. Hierarchical Planning
     - Ignore detail when possible

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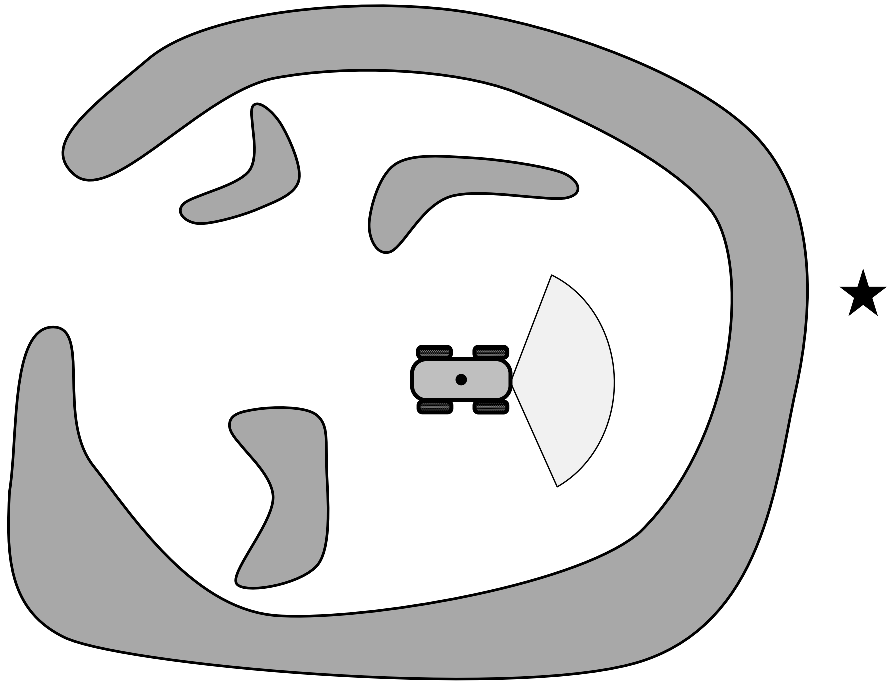
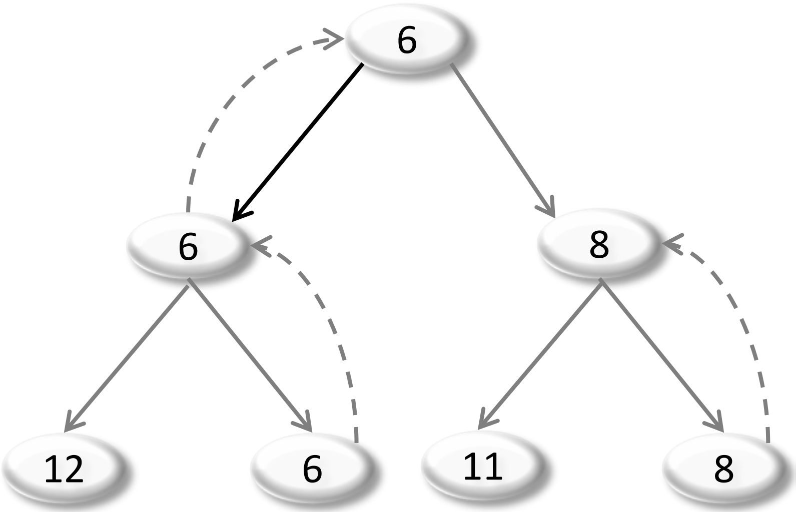
10.3.2.1 Purely Reactive Planning



- Search is conducted physically with the robot.
  - Bias toward goal added
- However, the right answer (above) is to move away from the goal for a while.
- Cyclic behavior is a common failure mode.

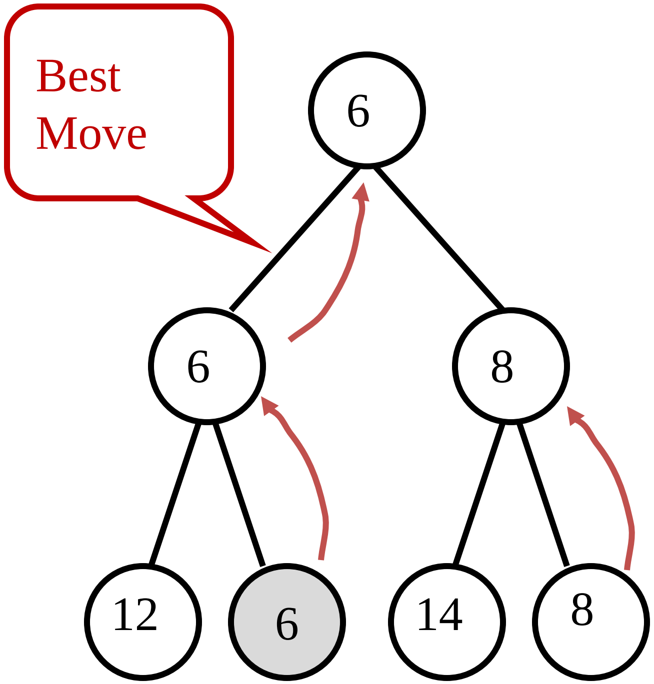
10.3.2.2 Depth Limited Planning

- Same as receding horizon predictive control.
- Propagate best child up the tree …
- Then, takes the first step toward the best leaf.
- and repeat.



10.3.2.3 Real Time A* (Korf)

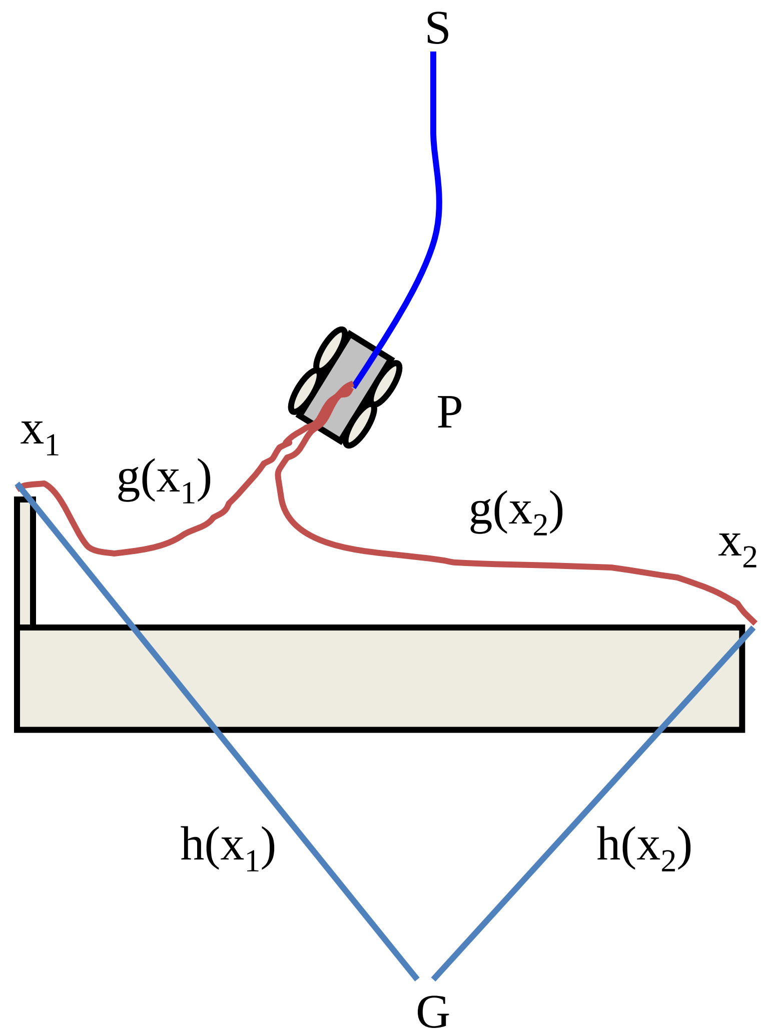
- MiniMin lookahead search:
  - Search forward some fixed depth determined by the available computation.
  - Compute the "backed" up value of each potential first move as the minimum heuristic value of all of its children on the search frontier.
  - Employ the principle of least commitment by making a single move to the best child of the current node.



Equivalent to simply **finding the best leaf node** and the first move toward it.

Real Time A* (Korf)

- In RTA* we re-interpret g(X) to mean the cost to get from the current state to state X rather than the cost from the original initial state - which is irrelevant once motion takes place.
- Net effect is to permit physical backtracking to an earlier visited state if the benefit of doing so outweighs the cost.
- This planner and all unknown environment planners are subject to strategy waffling (cycles).



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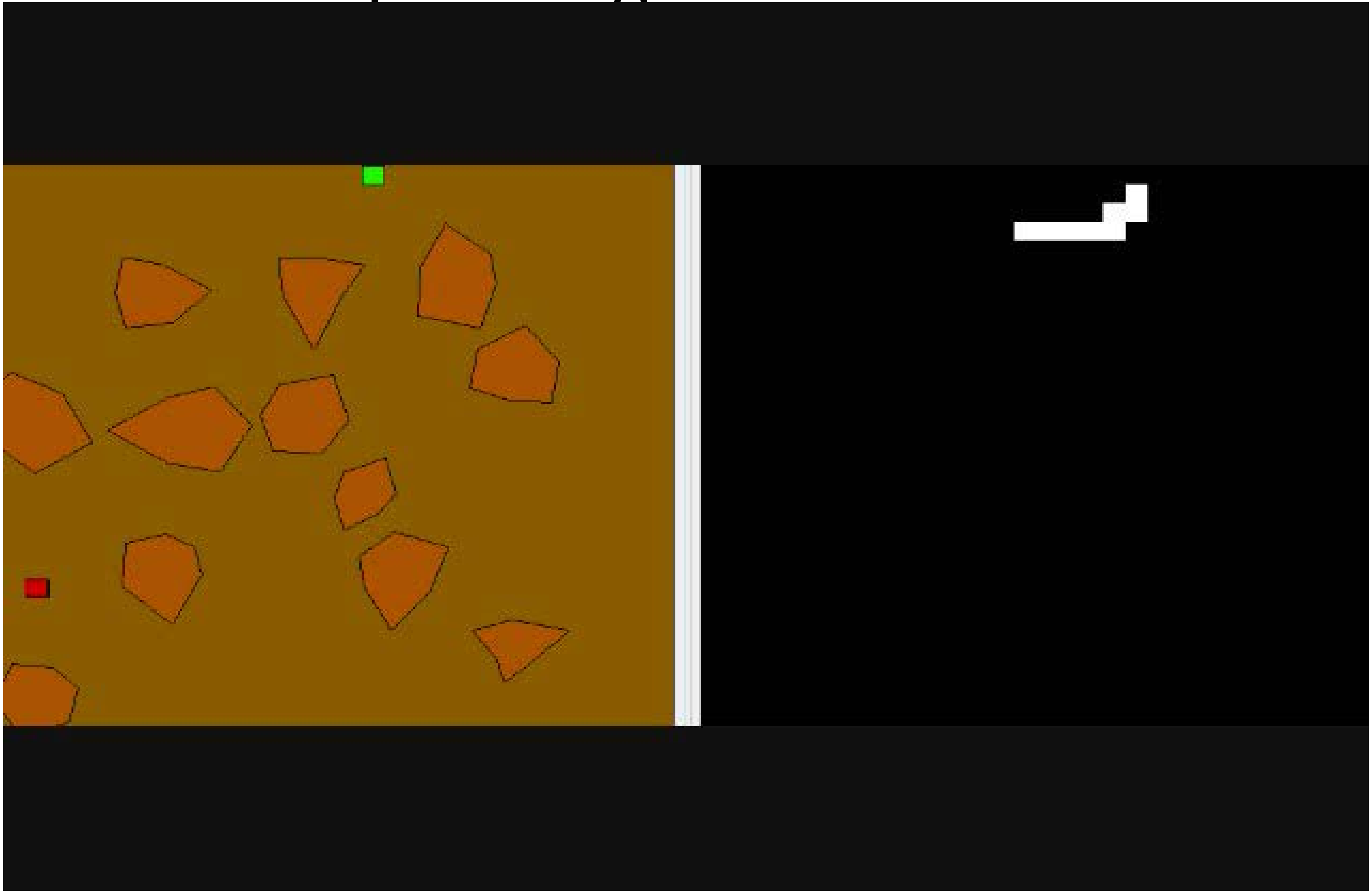
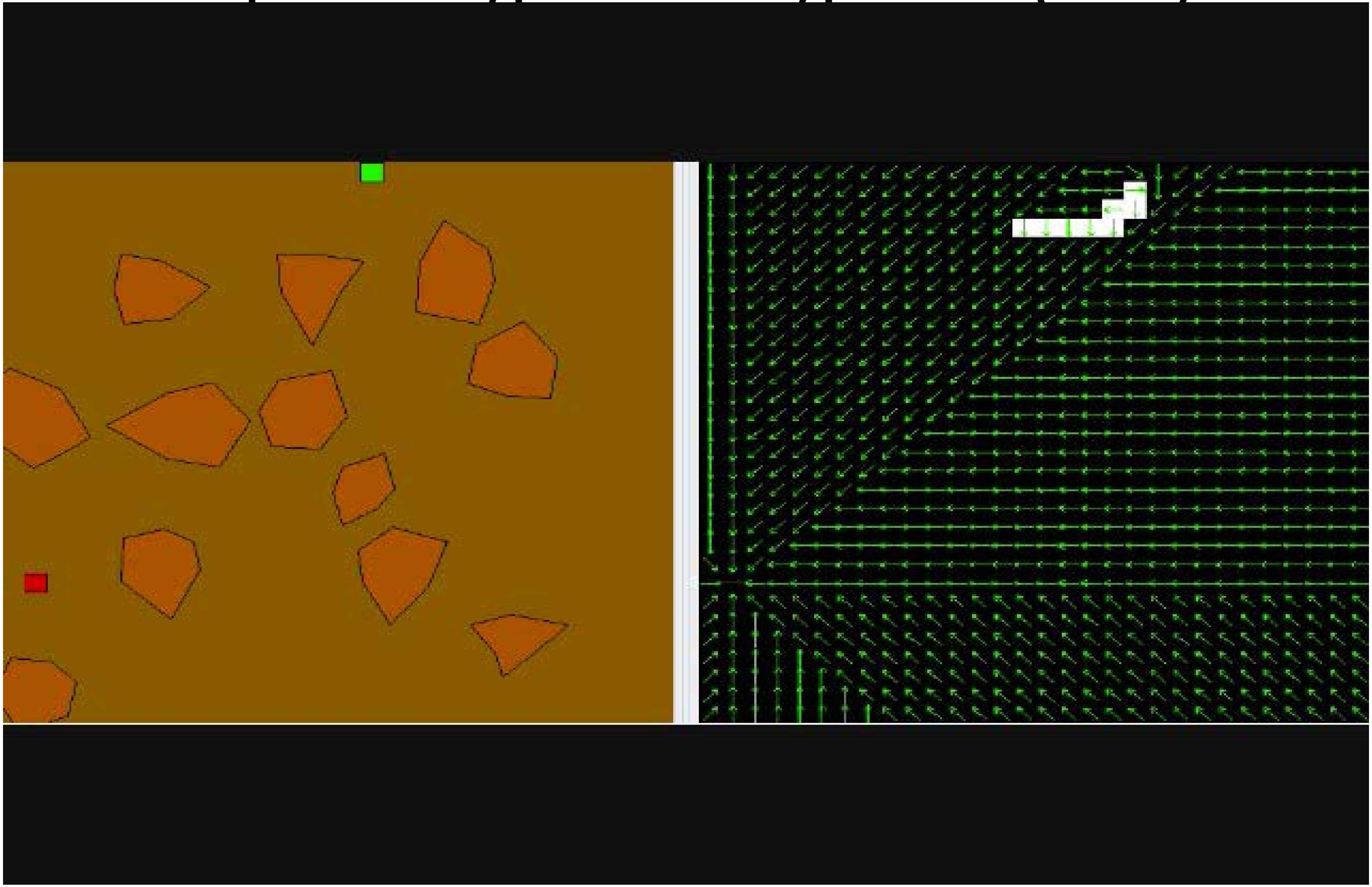
A* Replanning is Still Too Slow



Replanning Done Right D* (Lite)

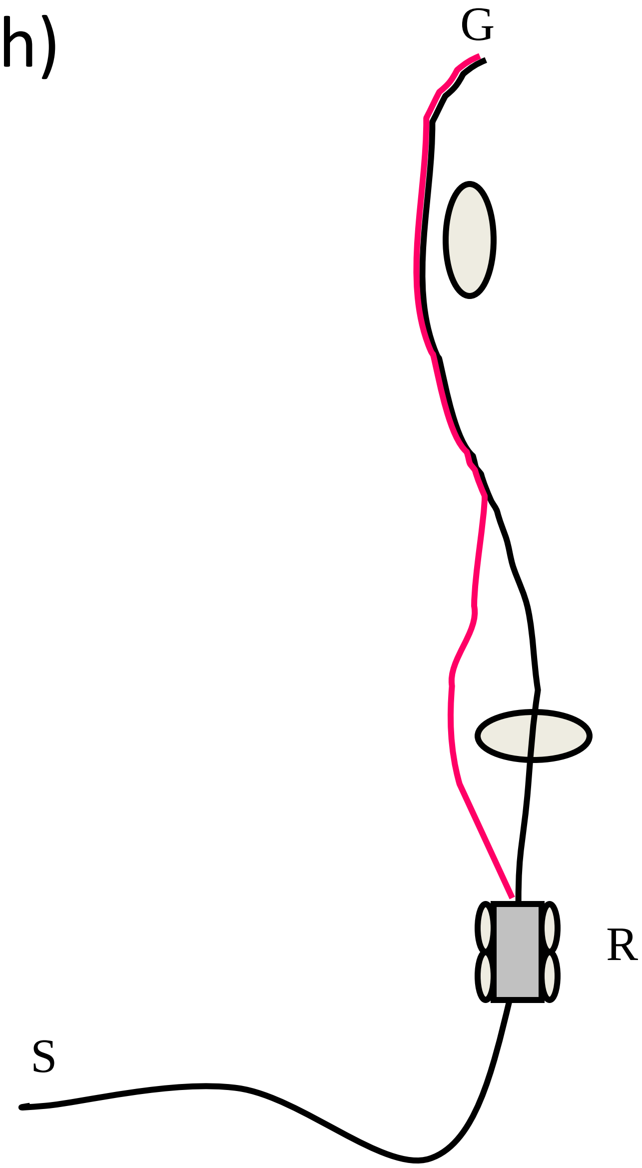


10.3.4 Plan Repair Approach: D* Algorithm

(Basic Approach)

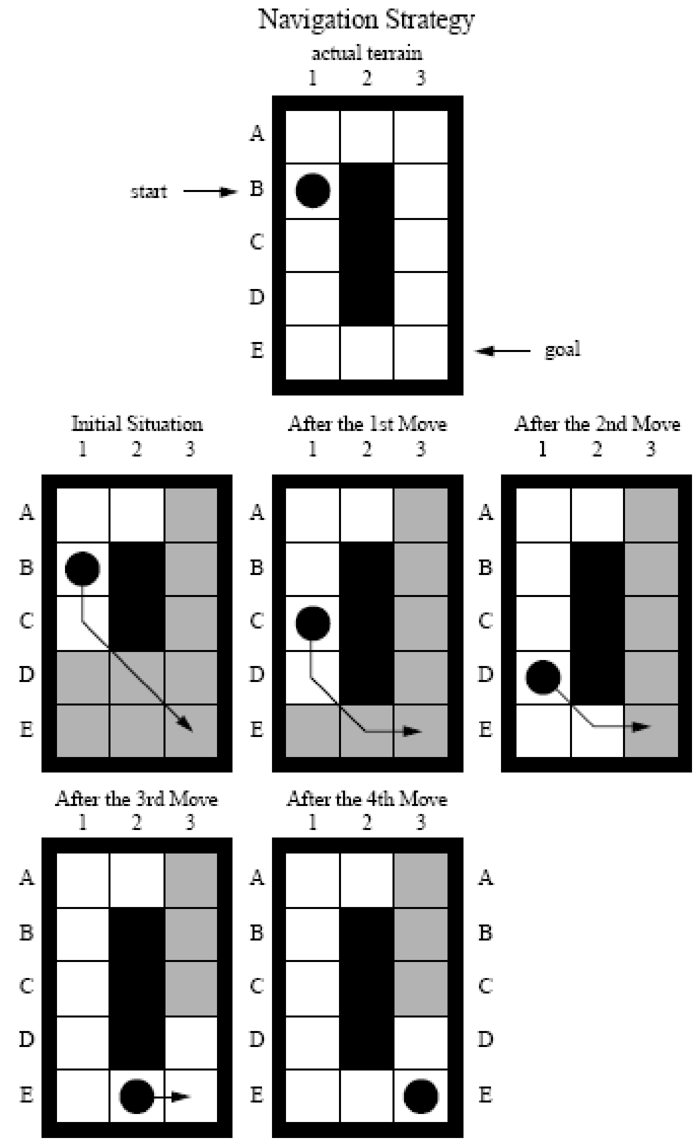
- Construct an initial solution using A* (or whatever).

- Continuously maintain this solution as….
  – 1: New information arrives
  – 2: The robot moves.



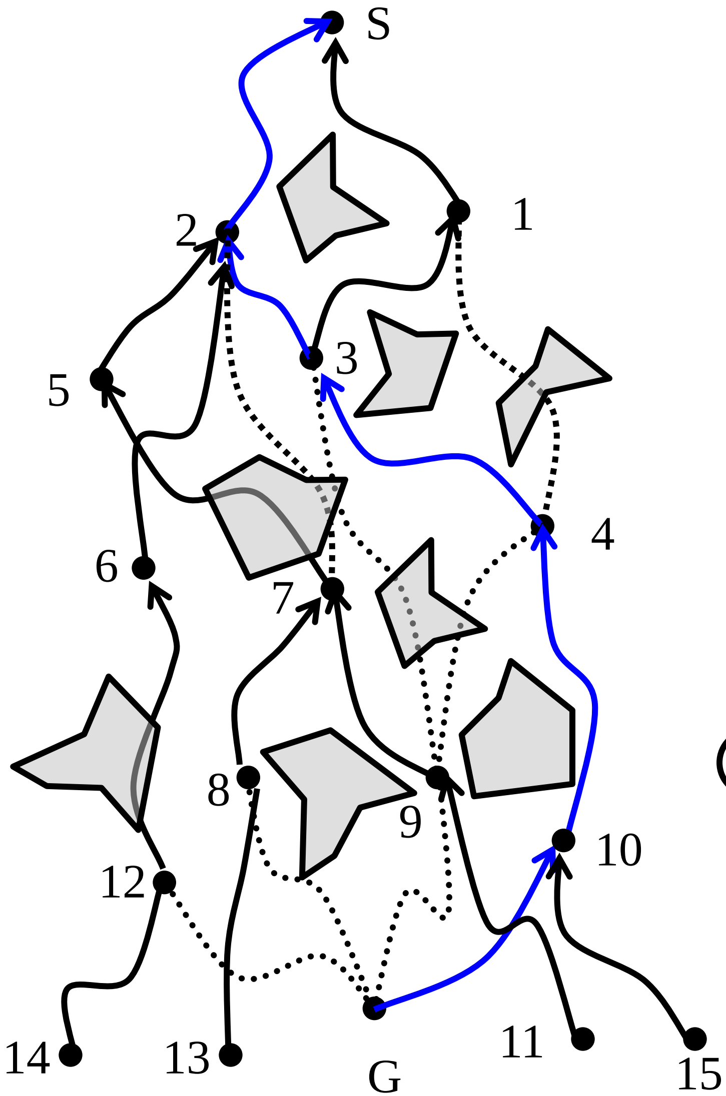
10.3.4 Plan Repair Approach: D* Algorithm
(Basic Approach)

- 1: Compute initial path up front.
- 2: Follow path until something new is learned.
- 3: Propagate the changes through search tree.
- 4: Compute new path
- 5: Goto 2:

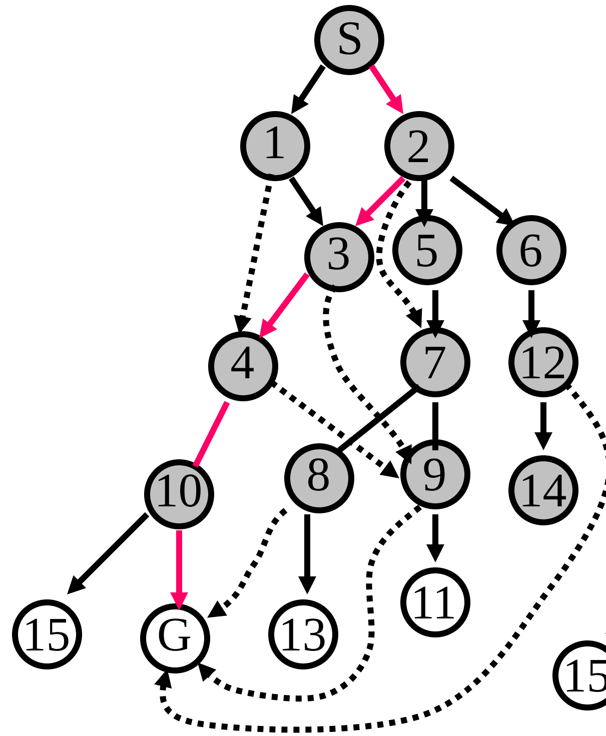


10.3.4 Plan Repair Approach: D* Algorithm

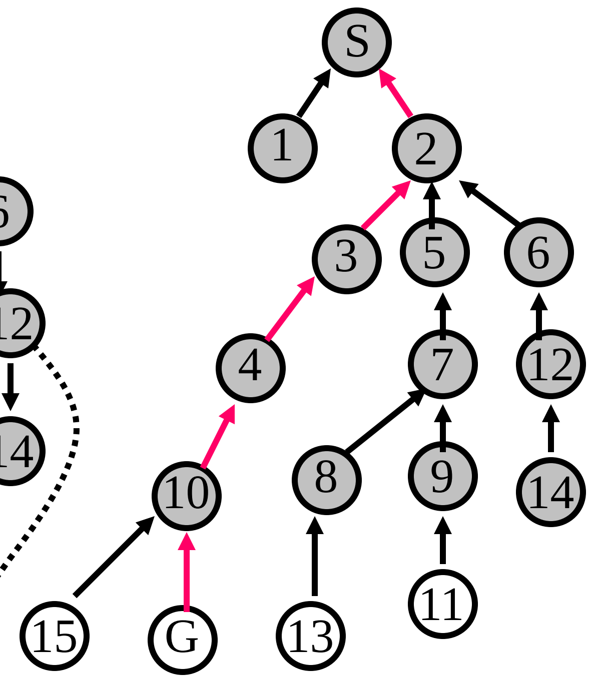
(Search Graph Vs Tree)



Search Graph



Search Tree



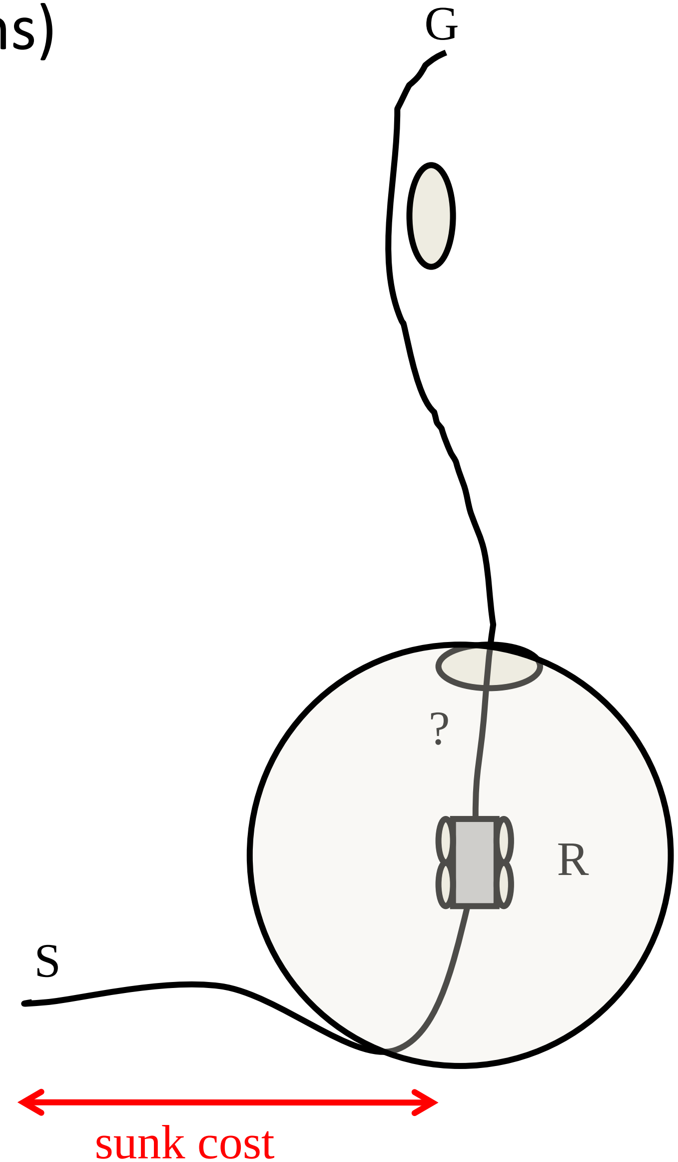
Downward arrows are graph elaboration point parent → child

Upward arrows are backpointers point child → parent

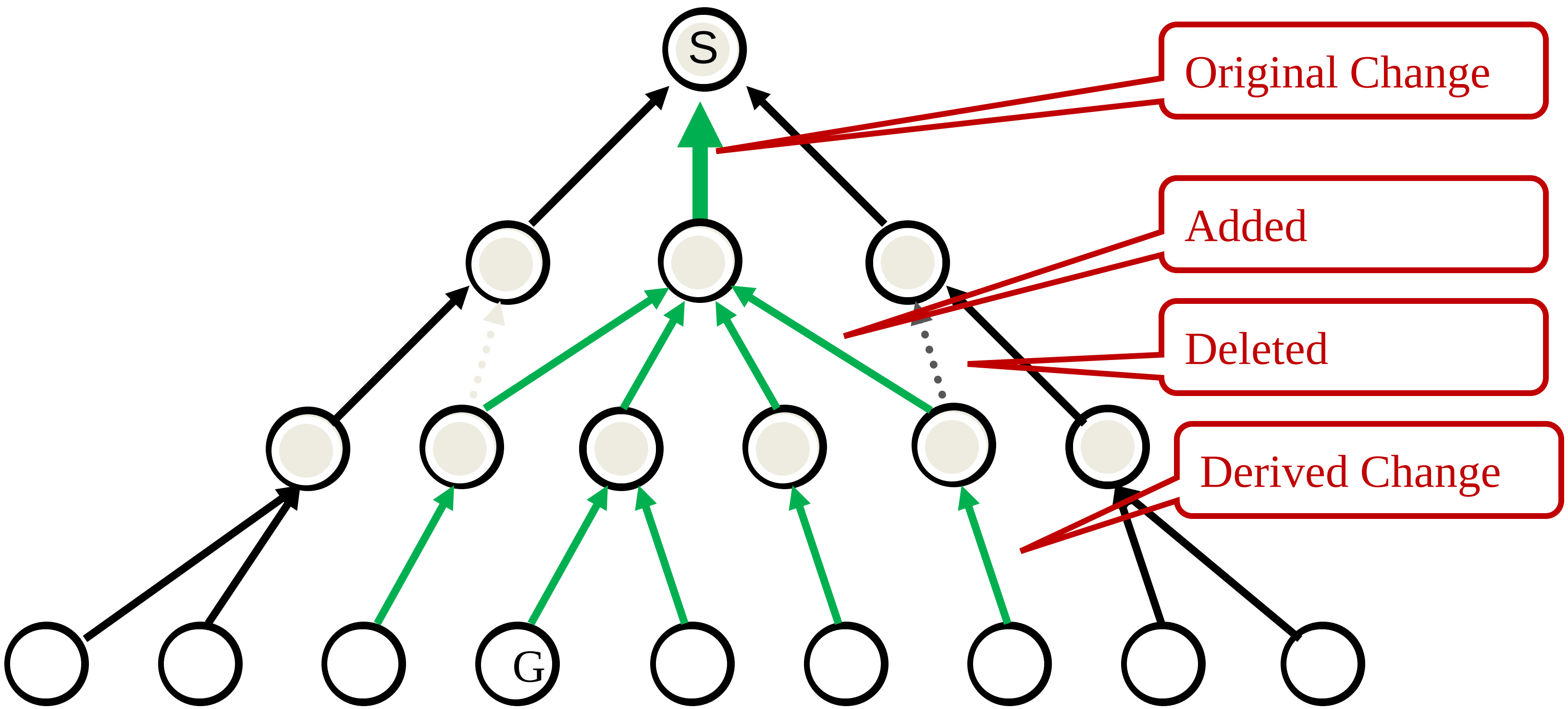
10.3.4 Plan Repair Approach: D* Algorithm
(Some Observations)

1. Only the path from here (not from start) to the goal is needed.

2. Discoveries are generally made close to the robot.



10.3.4 Plan Repair Approach: D* Algorithm (Propagating Cost Changes)

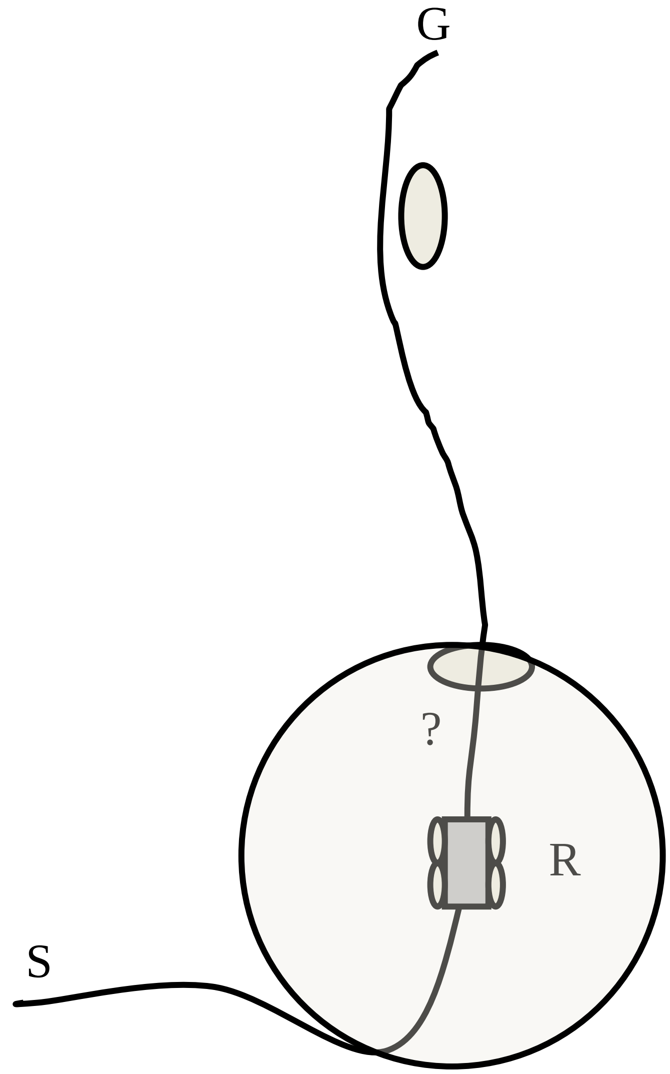


- Changes must propagate all the way to all pertinent affected leaves of the search tree

10.3.4 Plan Repair Approach: D* Algorithm (Conclusions)

- Since changes to a search tree must propagate all the way to the leaves to fully understand their implications ……

- Search from the goal BACKWARD to the robot.
  - Root = Goal
  - Leaf = Robot

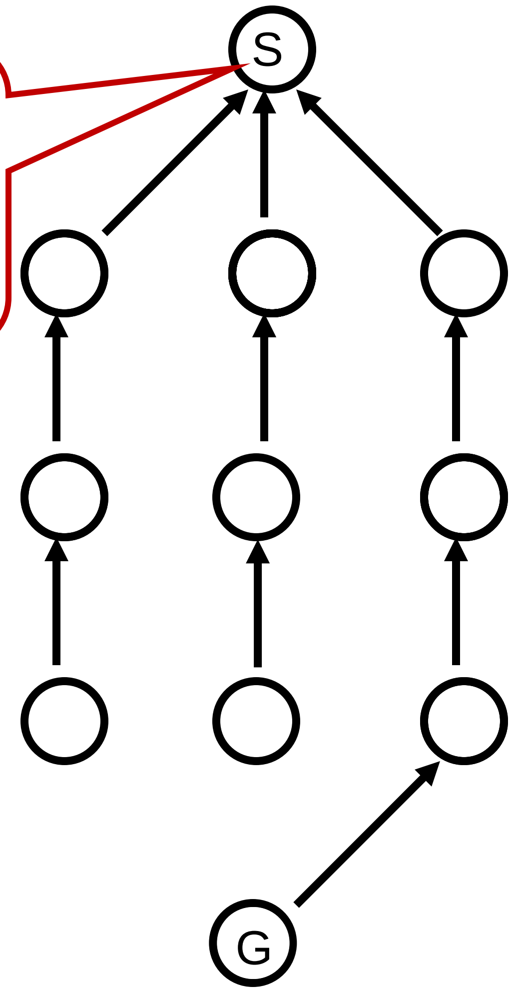


10.3.4 Plan Repair Approach: D* Algorithm

(Compute initial Path)

- Use A* from G (goal) to R (robot). Save f() values of every node opened.
- Dstar: Work in terms of h() and k() where:
  - h() is same as f() in A*
  - k() is the minimum value h() has ever had since it was placed on OPEN.
- DstarLite: Work in terms of g() and rhs() where:
  - g is same as before
  - rhs is best possible g RIGHT NOW based on all possible neighbors

Now the GOAL is the root of the search tree **but I call it S** for cleaner code.

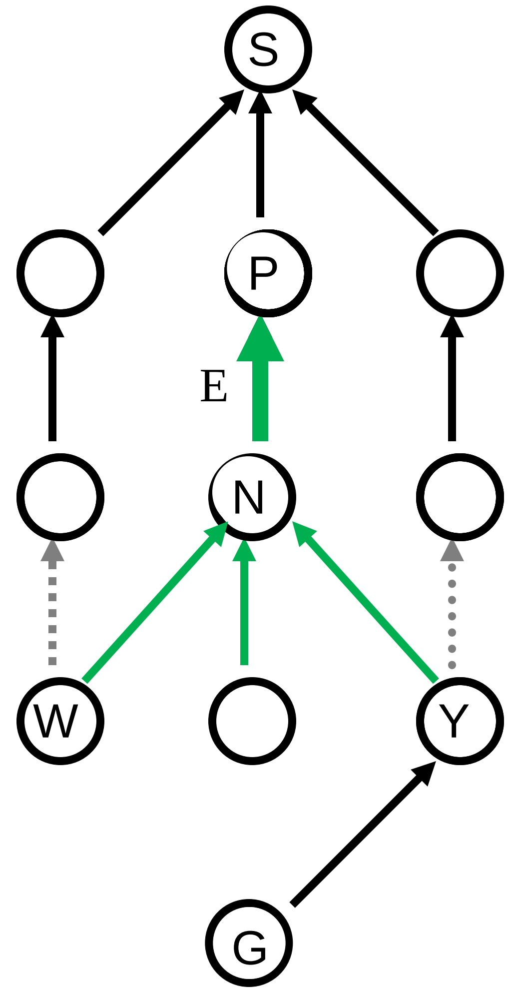


This is the search tree → spanning tree encoded in backpointers.

10.3.4.1.2 Implications of Edge Changes

(Lowered Cost)

- Suppose an edge E gets cheaper….
- Nodes W and Y may want to abandon their parents in favor of N.

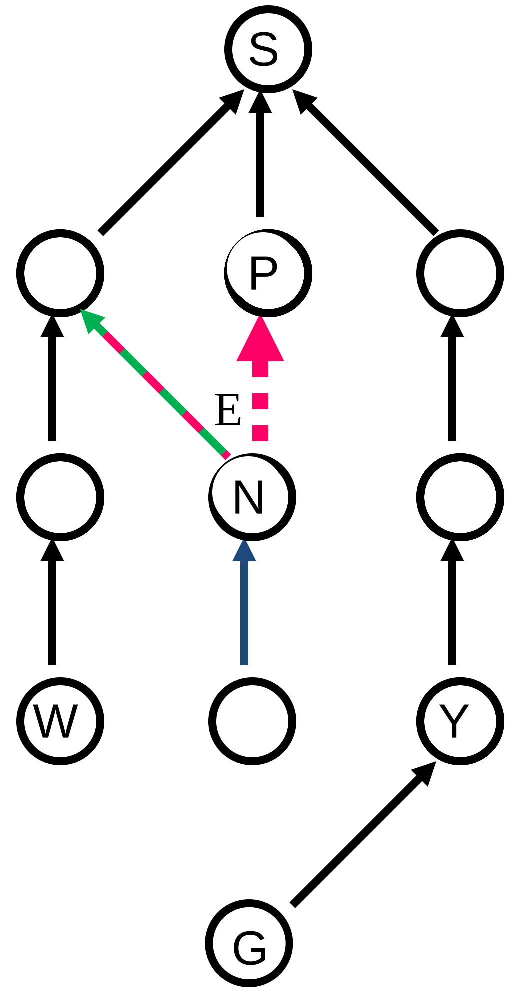


This is the search tree → spanning tree encoded in backpointers.

10.3.4.1.2 Implications of Edge Changes

(Raised Cost)

- Suppose an edge gets costlier….
- Node N may want a different parent.

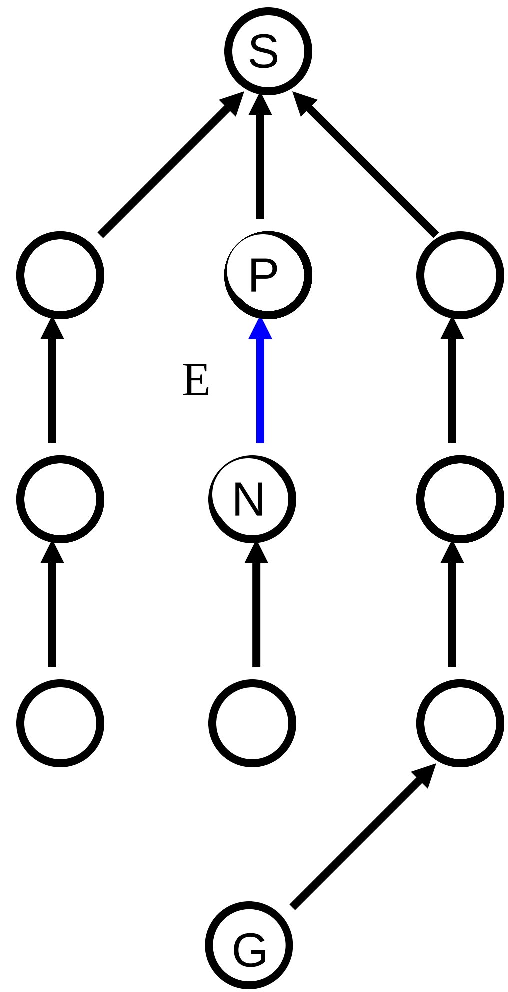


This is the search tree → spanning tree encoded in backpointers.

10.3.4.1.2 Implications of Edge Changes
(Efficient Propagation)

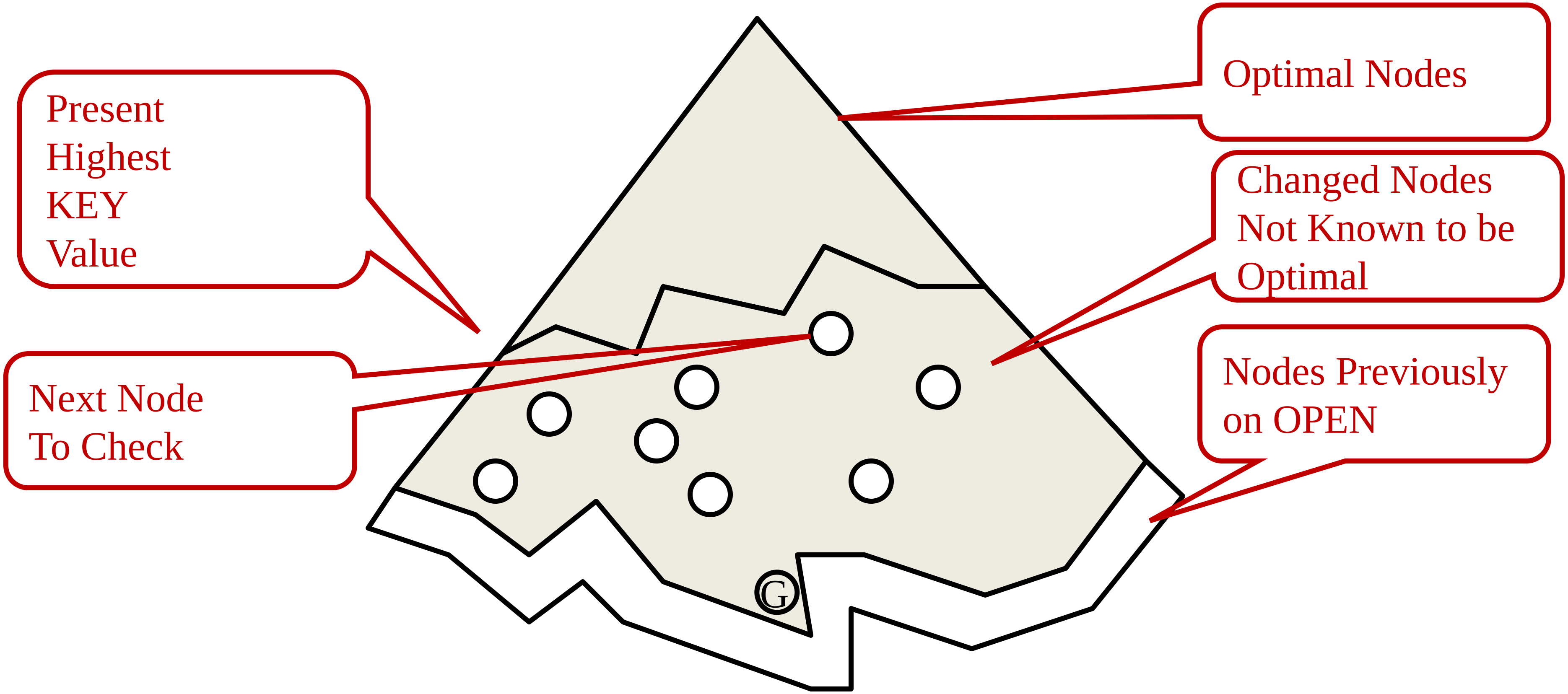
- (Almost) Brute force approach:
  - Go back in time….
  - Remove all nodes from OPEN or CLOSED for which f(Node) > f(P).
  - Mark remaining leaves as open
  - Rerun Astar.
- Efficient?
  - Touches every node between P and G in the solution tree.
  - Many end up unchanged from last time.
- Not efficient.

- BUT: Placing affected nodes on OPEN is a good idea.
  - See next figure to visualize.

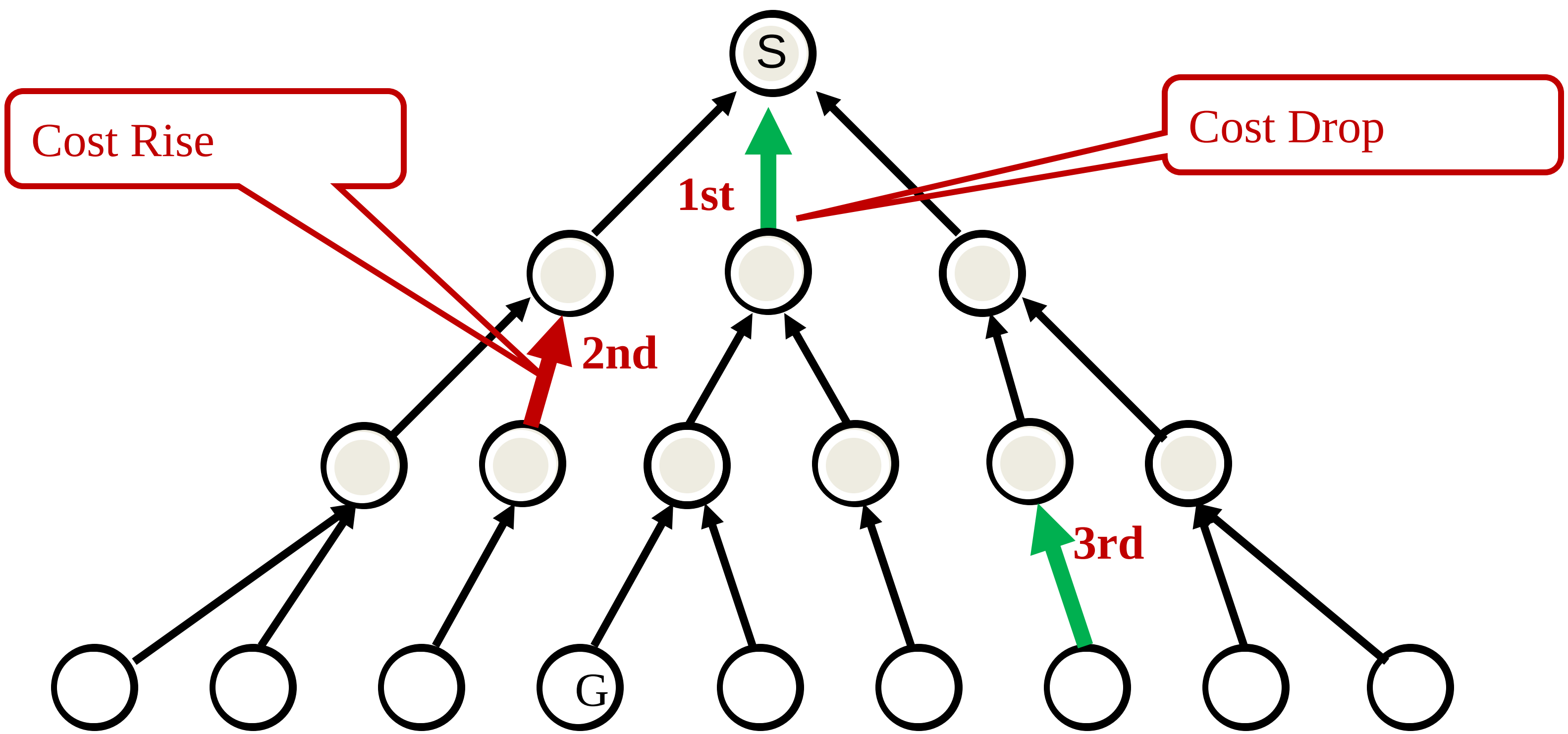


10.3.4.1.2 Implications of Edge Changes

(D* Processing Wavefront)



10.3.4.1.4 Processing Multiple Changes

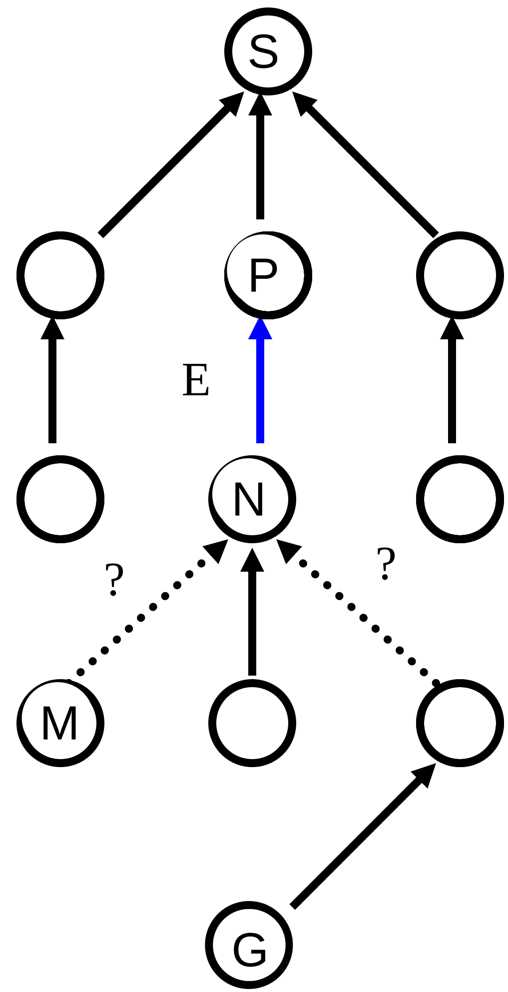


- Propagate changes downward in one pass committing as you go
  - Hence sort changed nodes (perhaps on OPEN?)
- Lowered states may need to move up the tree
  - Their sort key is their new cost (move up before the slot closes)
- Raised states may need to move down the tree
  - Their sort key is their old cost (move down before you get stuck)

10.3.4.1.4 Propagating Cost Changes

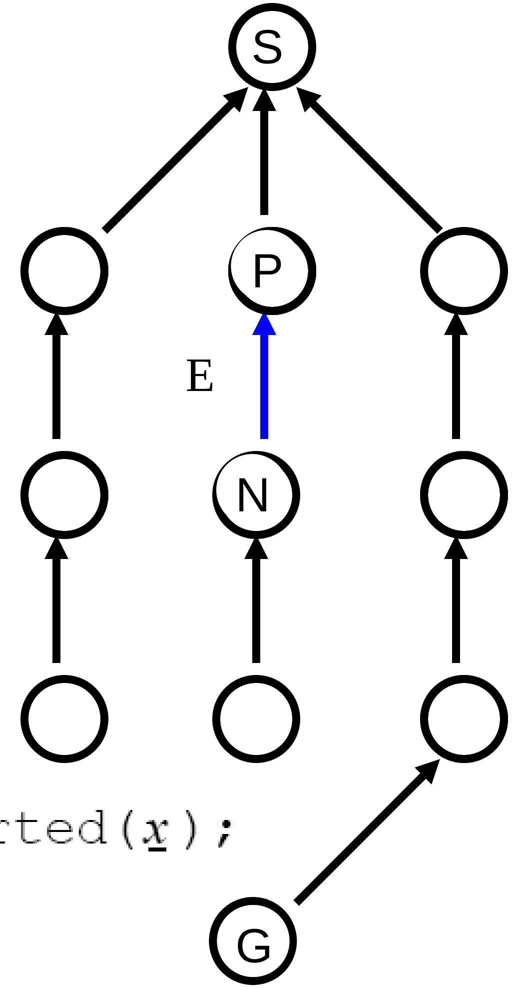
(Will Rerunning Astar Work?)

- Place N on OPEN and propagate changes downward (reopening closed nodes)
- Does not work.
  - In Astar, nodes on OPEN compete to be the parents of neighboring nodes.
  - The resulting subtree must have N as its root (N is like start).
  - So, every changed node will have a path that goes through N.
  - No mechanism for M to route around N if Edge E increased in cost.



Idea: Propagate Inconsistency

- Node N is inconsistent if it does not point to its “best” parent.
- Remove this node and, if it is not optimal, reinsert in O in correct place.




```
updateVertex(x){
    if( x != x_start ) getRhs(x);
    if( x ∈ O ) O.remove(x);
    if( g(x) ≠ rhs(x) ) O.insertSorted(x);
}
```

Dstar Lite Goodies

- "Right Hand Side"

$$rhs(s) = \begin{cases} 0 & \text{if } s = s_{start} \\ \min_{s' \in Pred(s)}(g(s') + c(s', s)) & \text{otherwise.} \end{cases}$$

Detects Inconsistent Nodes

  – It's the cost a node would have if one level of lookahead was resolved.

- "Key" (f value)

Sorts Properly For One Pass Resolution

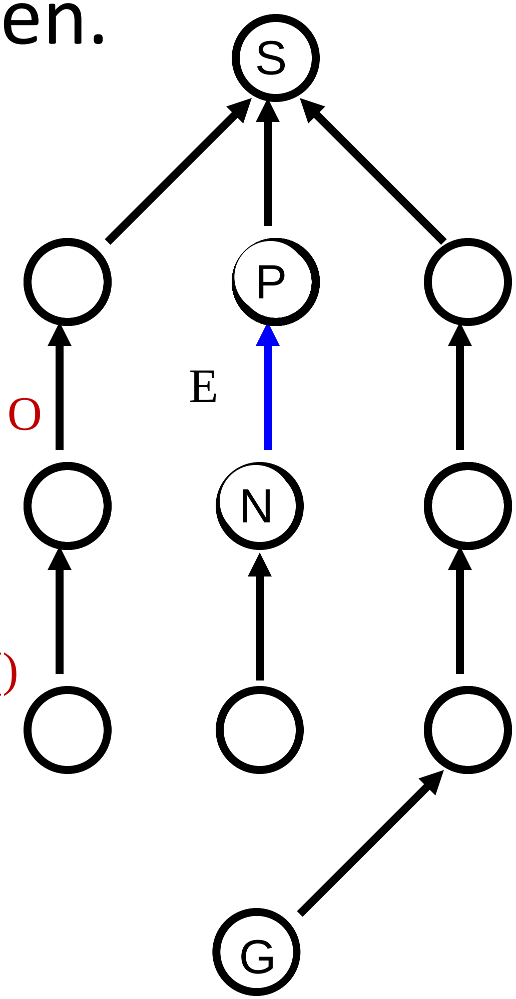
$$[\min(g(s), rhs(s)) + h(s, s_{goal}); \min(g(s), rhs(s))]$$

  – Cost a node will have as soon as its neighbors are told they need to change.
  – Break ties with second key.

Idea: Propagate Inconsistency

- Check all neighbors of nodes on open.

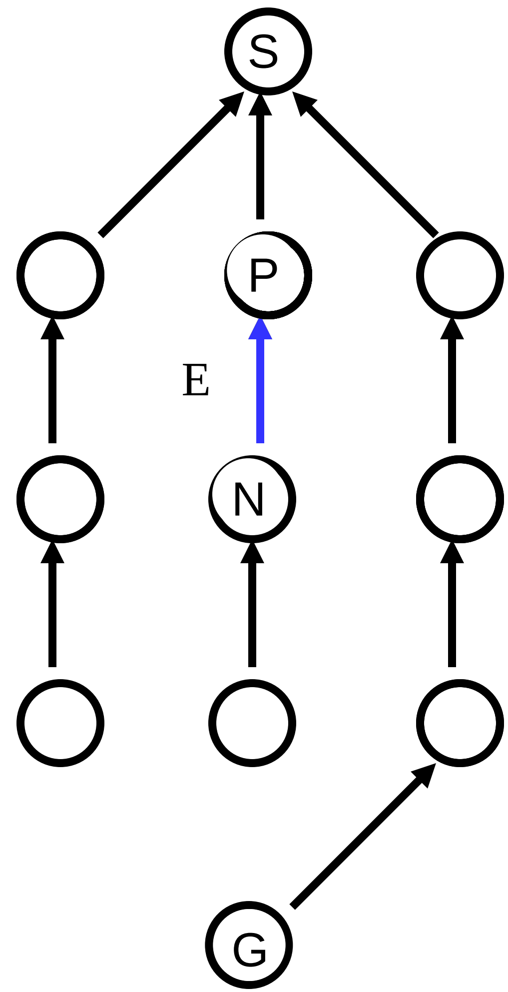
```
computeShortestPath(x){
    while(f[O.peek()] < f(x_goal) || g(x_goal) ≠ rhs(x_goal) )
        x_next = O.pop();                         Remove from O
        if( g(x_next) > rhs(x_next) ){            g is too high
            g(x_next) = rhs(x_next);              Correct it, don't put it back on O
            for(each x_neigh ∈ pred(x_next))      Check all neighbors
                updateVertex(x_neigh);
        } else {                                  g is OK or too low
            g(x_next) = ∞                         Force it on O with key based on rhs()
            for(each x_neigh ∈ pred(x_next) ∪ {x_next})
                updateVertex(x_neigh);            Check all neighbors
        }
}
```



Termination

- Terminate when:
  - lowest f() on OPEN > f(robot)
  - Robot node is then optimal.

- Often need to compensate for roundoff:
  - lowest f() on OPEN > f(robot) + e



Entire Algorithm

```
procedure CalcKey(s)
  return [min(g(s), rhs(s)) + h(s_start, s); min(g(s), rhs(s))];
procedure Initialize()
  U = ∅;
  for all s ∈ S rhs(s) = g(s) = ∞;
  rhs(s_goal) = 0;
  U.Insert(s_goal, CalcKey(s_goal));
procedure UpdateVertex(u)
  if (u ≠ s_goal) rhs(u) = min_{s' ∈ Succ(u)} (c(u, s') + g(s'));
  if (u ∈ U) U.Remove(u);
  if (g(u) ≠ rhs(u)) U.Insert(u, CalcKey(u));
procedure ComputeShortestPath()
  while (U.TopKey() <· CalcKey(s_start) OR rhs(s_start) ≠ g(s_start))
    u = U.Pop();
    if (g(u) > rhs(u))
      g(u) = rhs(u);
      for all s ∈ Pred(u) UpdateVertex(s);
    else
      g(u) = ∞;
      for all s ∈ Pred(u) ∪ {u} UpdateVertex(s);
procedure Main()
  Initialize();
  ComputeShortestPath();
  while (s_start ≠ s_goal)
    /* if (g(s_start) = ∞) then there is no known path */
    s_start = arg min_{s' ∈ Succ(s_start)} (c(s_start, s') + g(s'));
    Move to s_start;
    Scan graph for changed edge costs;
    if any edge costs changed
      for all directed edges (u, v) with changed edge costs
        Update the edge cost c(u, v);
        UpdateVertex(u);
      for all s ∈ U
        U.Update(s, CalcKey(s));
      ComputeShortestPath();
```

For Sorting OPEN

Initialize

Perception Info

Plan Paths

Initial A* - Like call

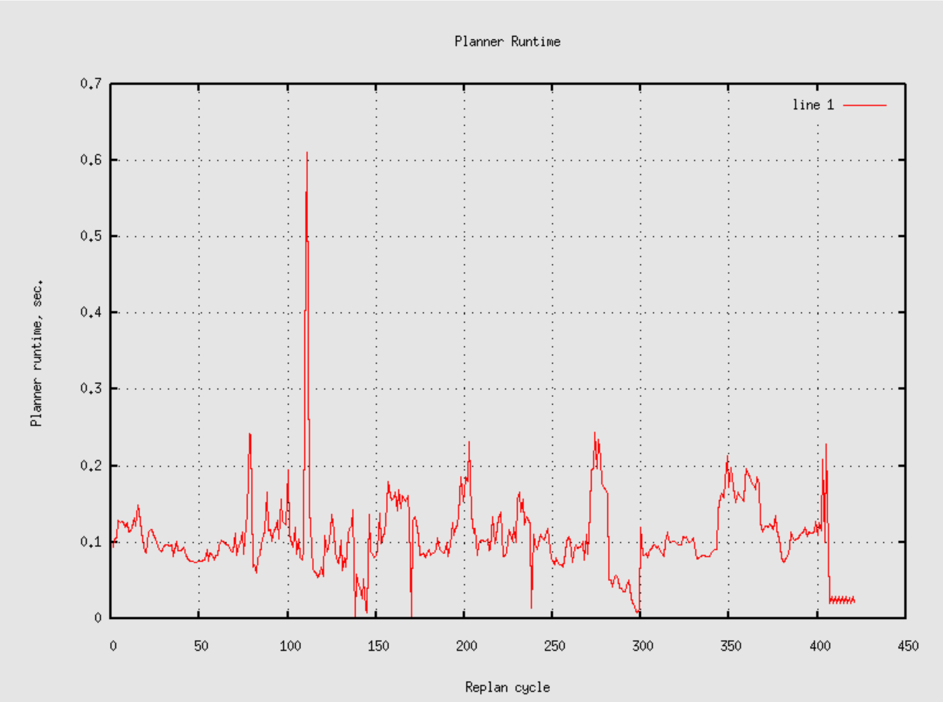
Move, Percieve, Replan

Beware

- Code switches GOAL and START for Dstar only.
- That means they are switched relative to the DstarLite paper.

Random Observations

- Runtime is not constant



- The alternative is worse.

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Summary

- The real motion planning problem is that of planning in dynamic and uncertain environments.
  – Maps are never completely accurate.
- Computational techniques are mature in the abstract case of grids.
- The real motion planning problems therefore become:
  – Understanding mobility
  – Adequate perception