15-494/694: Cognitive Robotics
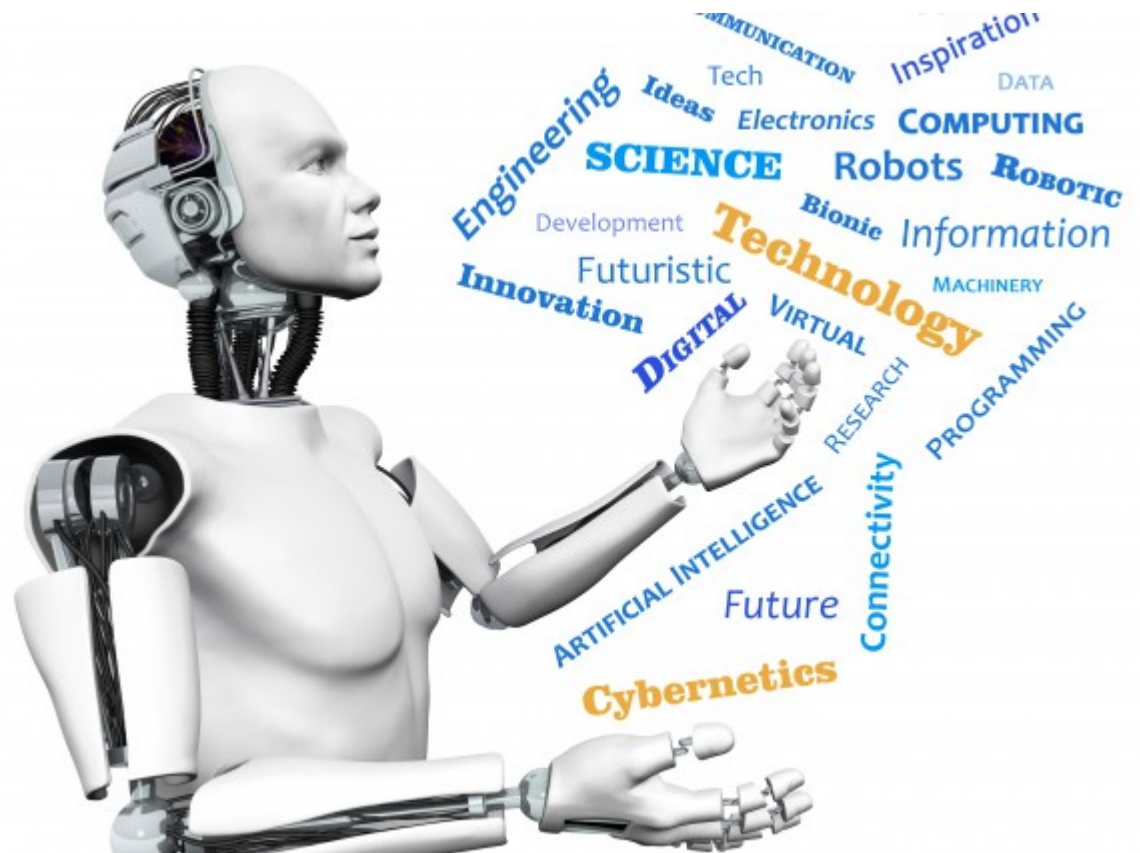
Dave Touretzky

Lecture 9:

Path Planning with
Rapidly-exploring
Random Trees

Navigating with the Pilot

Image from http://www.futuristgerd.com/2015/09/10

Outline

- How is path planning used in robotics?
- Path planning as state space search
- RRTs: Rapidly-exploring Random Trees
- The RRT-Connect algorithm
- Collision detection
- Smoothing
- Path planning with constraints
- Navigating with the Pilot

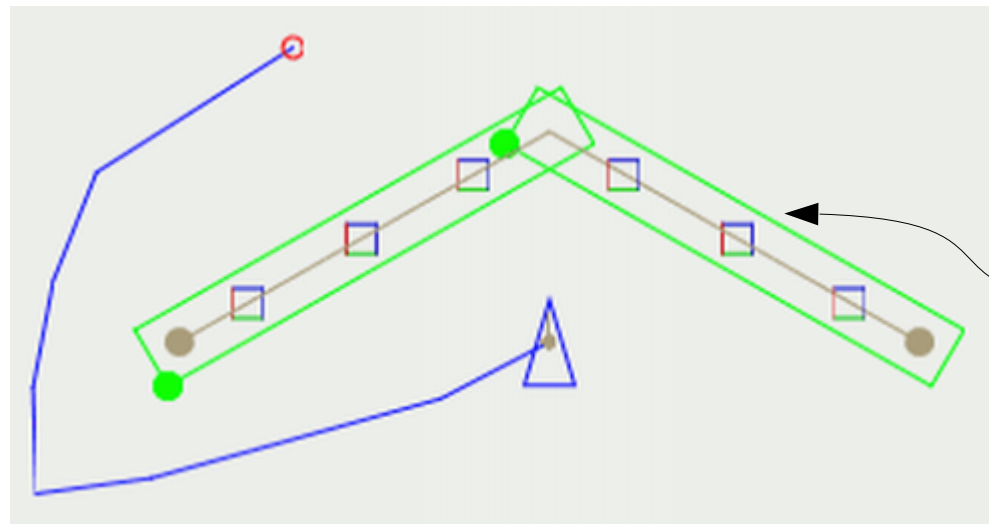# Path Planning in Robotics

1. Navigation path planning

   – How to get from the robot's current location to a goal.

   – Avoid obstacles.

   – Provide for localization.

2. Manipulation path planning

   – Move an arm to grasp and manipulate an object.

   – Avoid obstacles.

   – Obey constraints (e.g., don't spill the coffee).

Navigation Planning

- 2D state space: (x,y) coordinates of the robot

  – Treat the robot as a point or a circle.

Obstacle inflation

- 3D state space: (x,y,θ) pose of the robot

  – Heading matters when the robot is asymmetric

 – Heading matters when the robot's motion is constrained

Grid-Based Path Planning

- Discretizes the environment into a 2D grid.

- Wavefront algorithm: propagate from the start location.

- Can also use best-first or A* search.
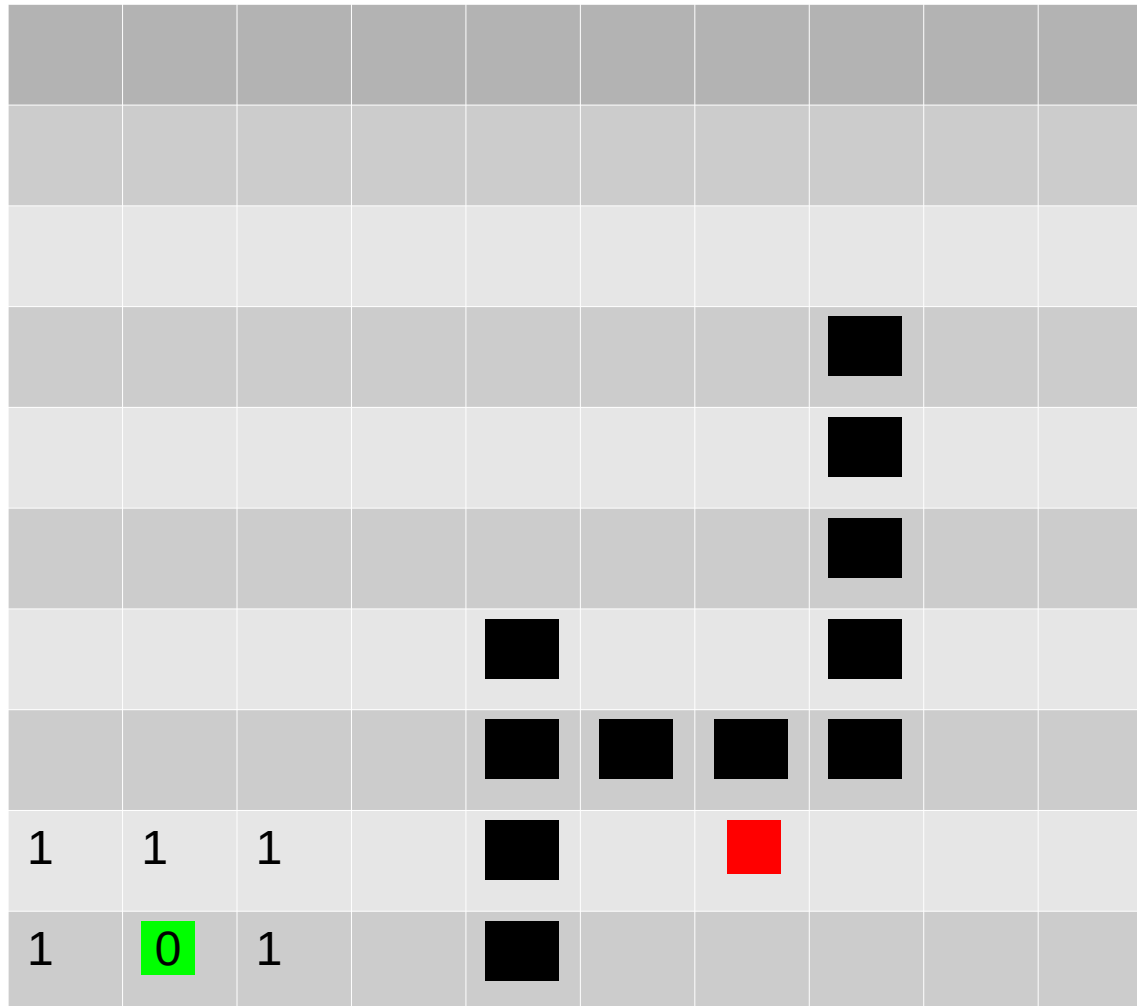
- Works okay in small spaces.

But it has its drawbacks:

- Treats the robot as a point. Unrealistic!
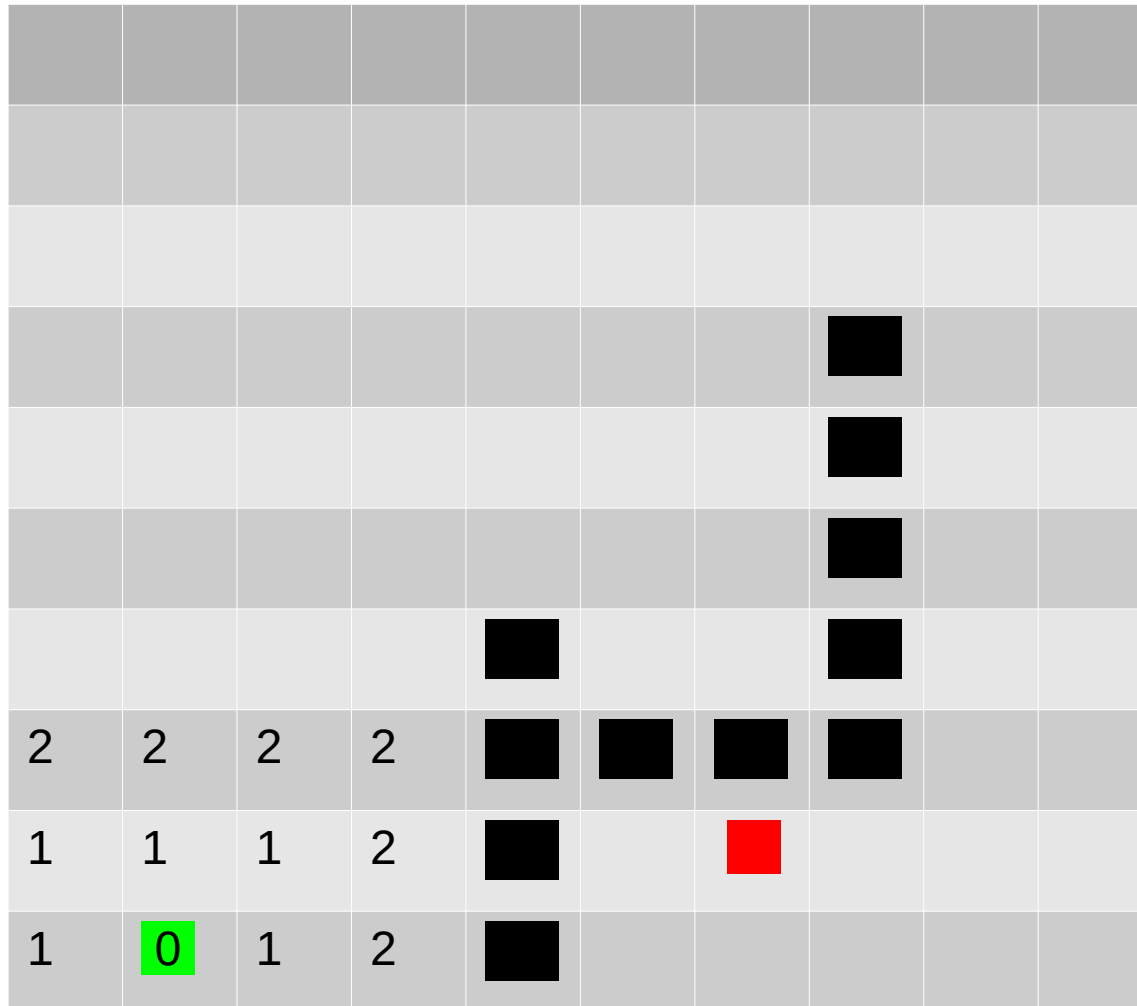
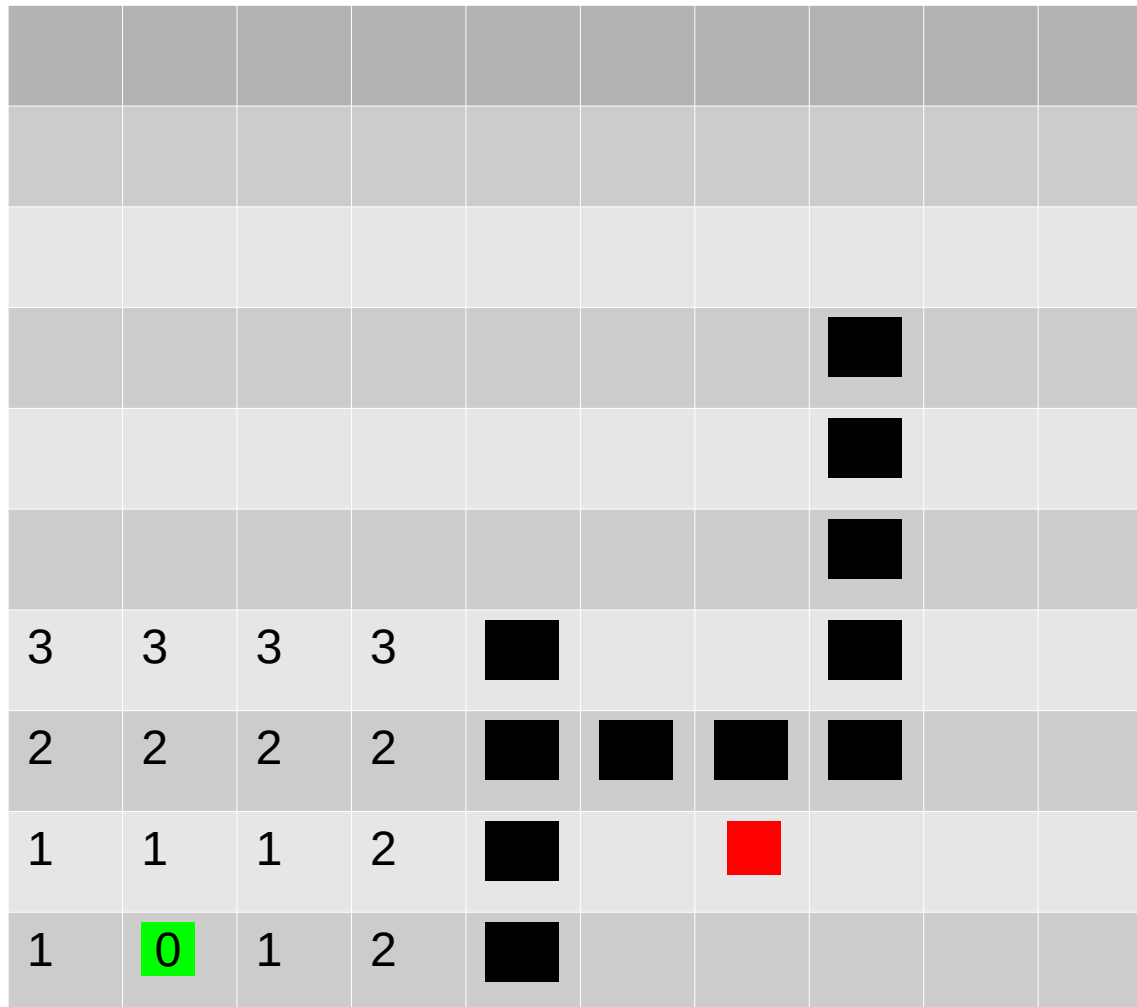- Not efficient in higher dimensional state spaces.
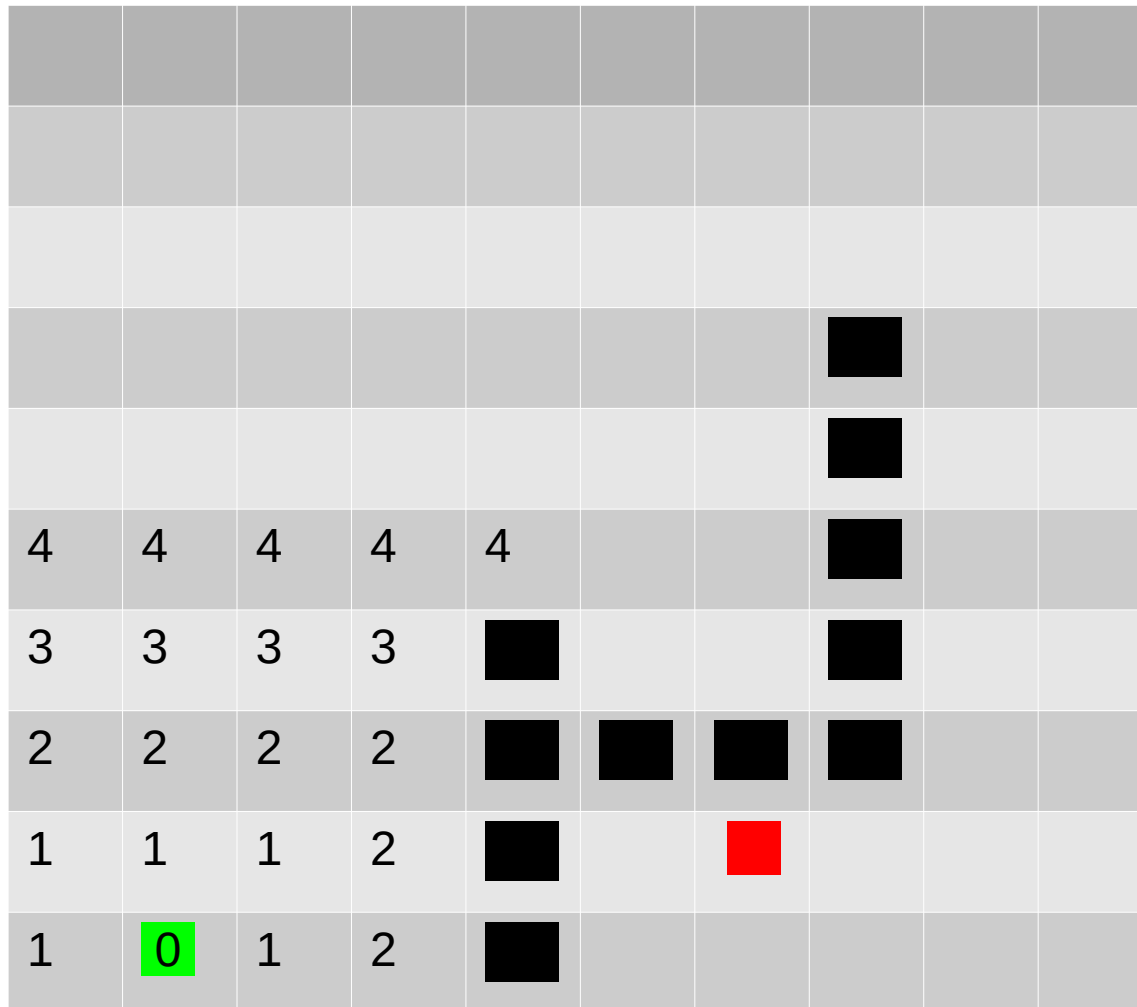
Wavefront Algorithm
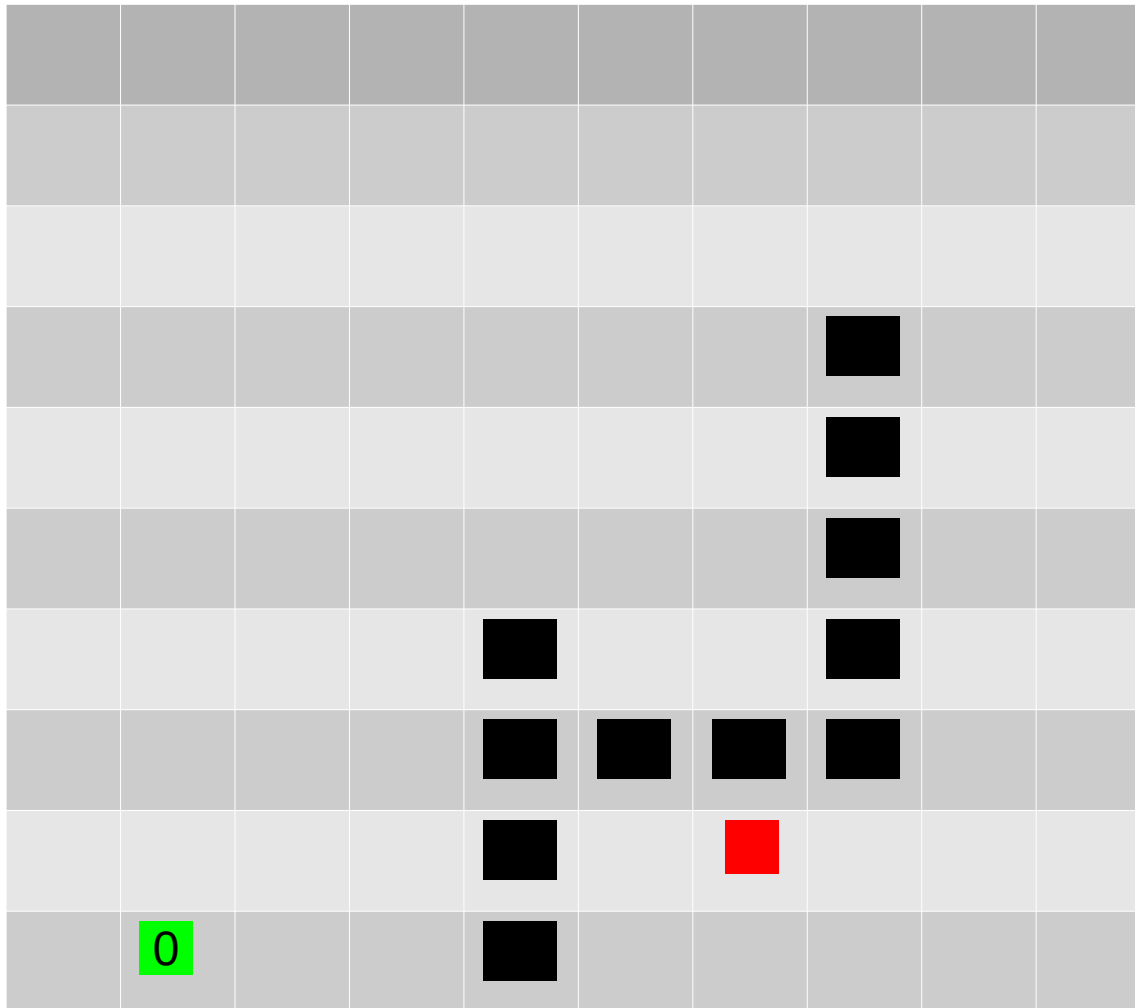
Wavefront Algorithm

Wavefront Algorithm

Wavefront Algorithm

Wavefront Algorithm

Wavefront Algorithm

9	9	9	9	9	9	9	9	9	10
8	8	8	8	8	8	8	8	9	10
7	7	7	7	7	7	7	8	9	10
6	6	6	6	6	6	7	■	9	10
5	5	5	5	5	6	7	■	10	10
4	4	4	4	■	6	7	■	11	11
3	3	3	3	■	7	7	■	12	12
2	2	2	2	■	■	■	■	13	13
1	1	1	2	■		15	14	14	14
1	0	1	2	■		15	15	15	15

Wavefront Algorithm

Best-First or A* Search

- Works okay in small spaces.

Same drawbacks as wavefront:

- Treats the robot as a point. Unrealistic!
- Not efficient in higher dimensional state spaces.

Best-First or A* Search Can Be Slow

- Can get trapped in a cul de sac for a long time.

- See search animation videos on YouTube.

- Random search might be faster.

Potential Field Path Planning

- Can fail due to local minima in the potential function.
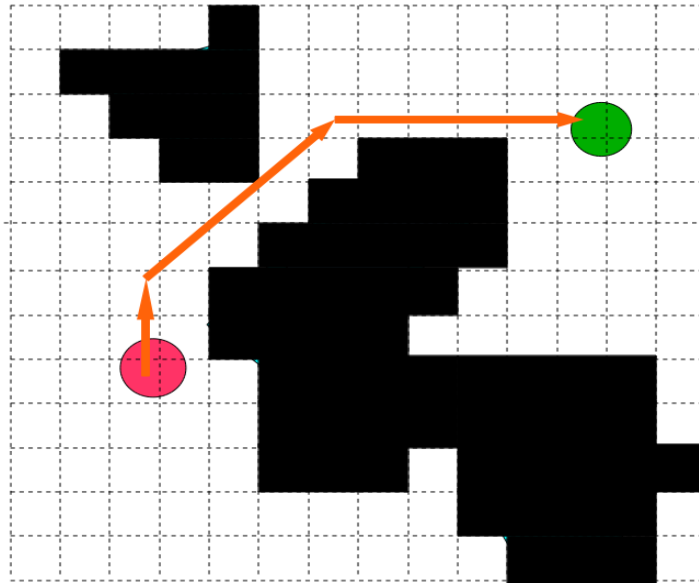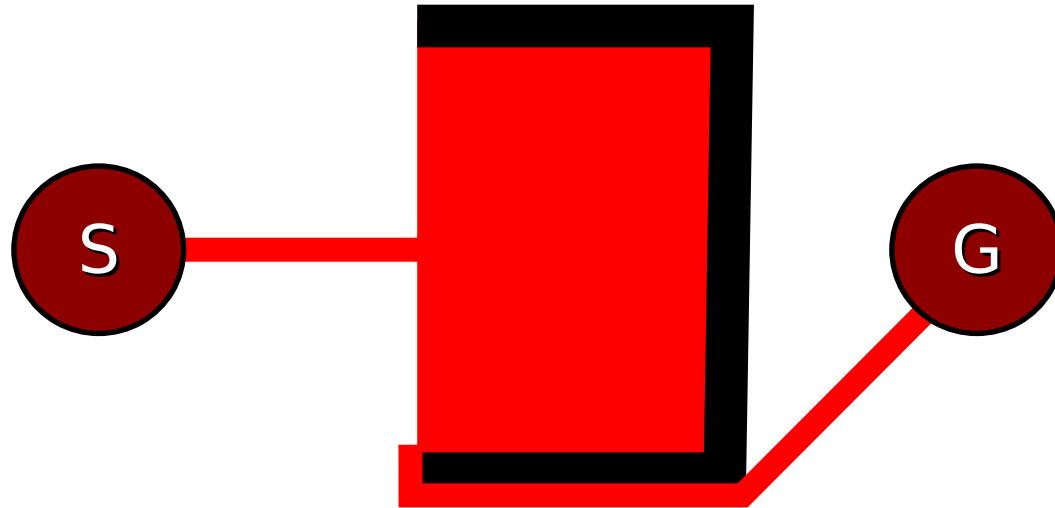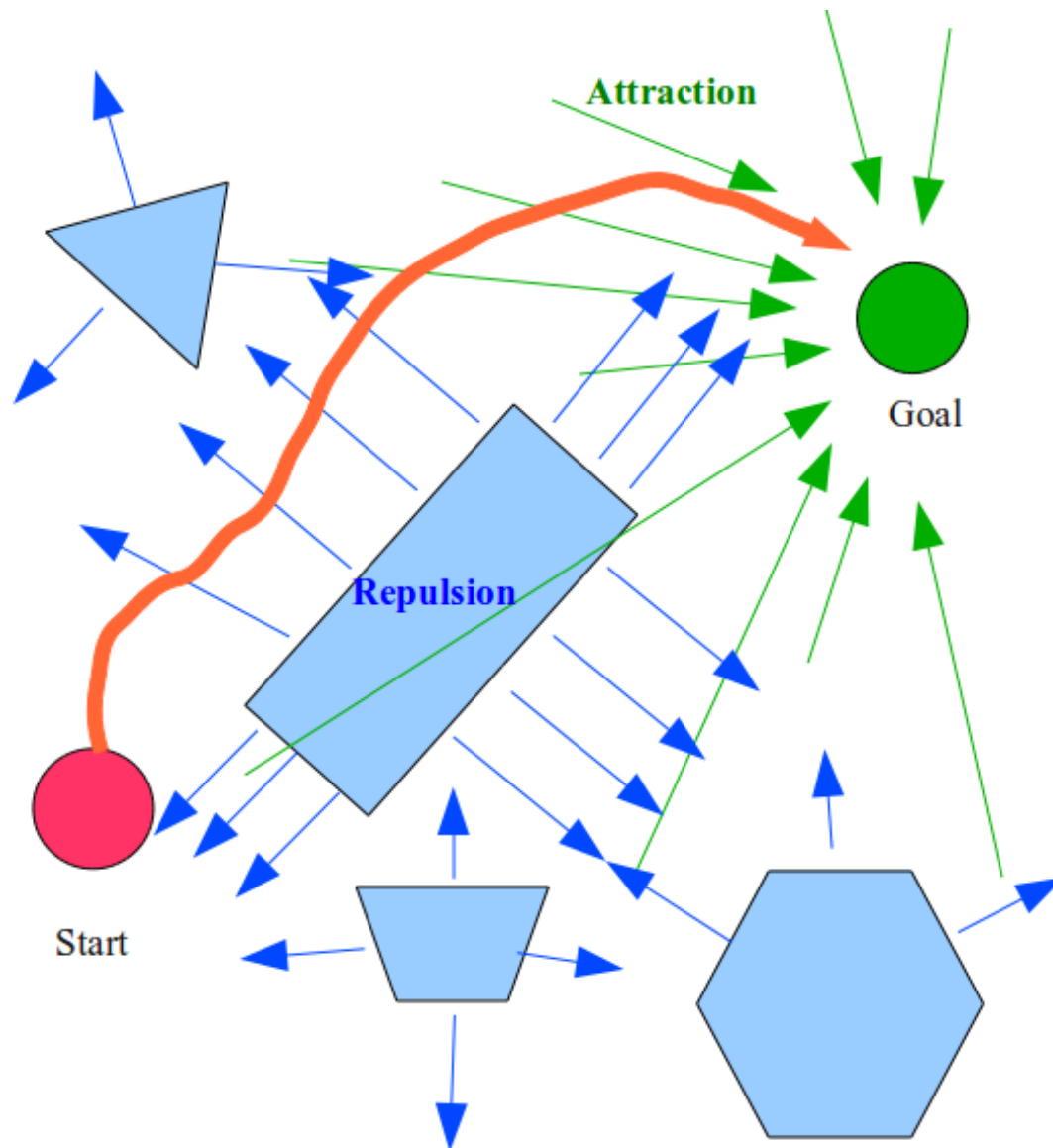
- Consider a U-shaped obstacle.

- Requires careful tuning.

Figure from http://www.gamasutra.com/blogs/MattKlingensmith/20130907/199787/Overview_of_Motion_Planning.php

Cspace Transform

- The area around an obstacle that would cause a collision with the robot.

Robot

Obstacle
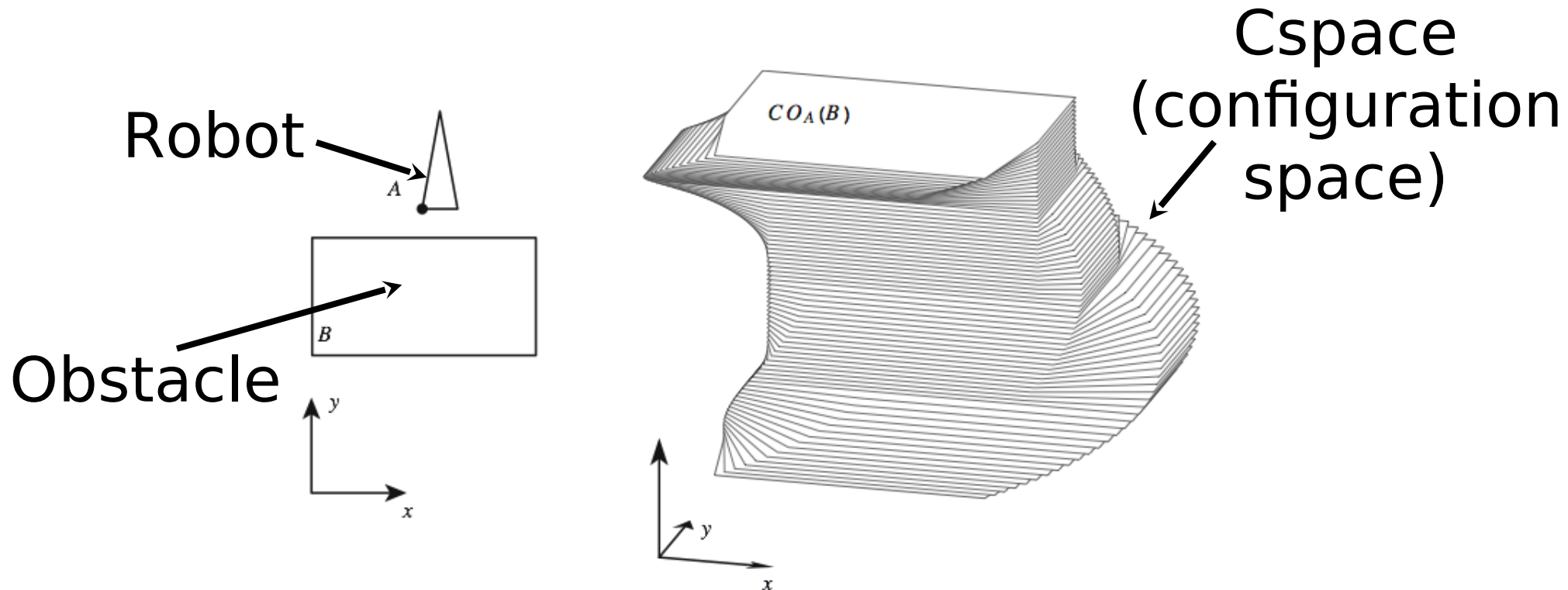
$CO_A(B)$

Cspace (configuration space)

Figure 4.4 - Mason, Mechanics Of Robotic Manipulation

Arm Path Planning

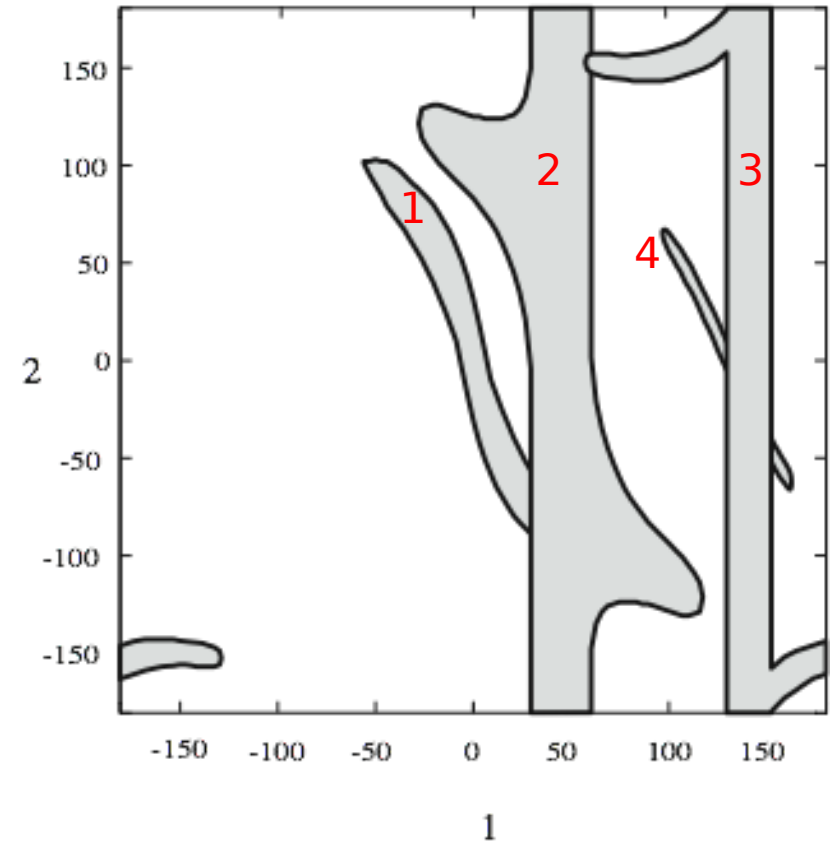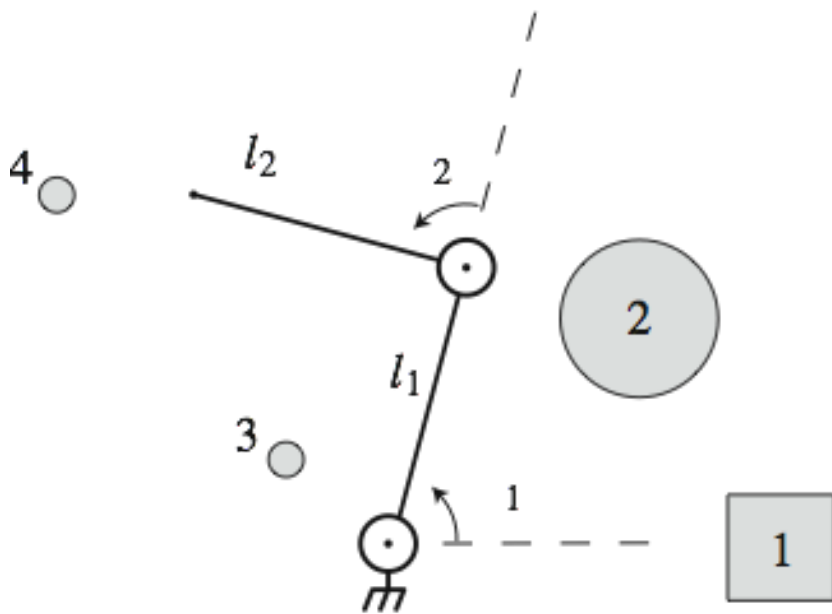- Cspace transform blocks out regions of joint space

Figure 4.5 - Mason, Mechanics Of Robotic Manipulation

State Space Search

The path planning problem:

Given an n-dimensional state space and

- a start state $S = <s_1, s_2, ..., s_n>$

- a goal state $G = <g_1, g_2, ..., g_n>$

- an admissibility predicate P (collision test + constraints)

find a path from S to G such that every state on the path satisfies P.

Rapidly-exploring Random Trees

- Described in LaValle (1998), Kuffner & LaValle (2000)

- Create a tree with initial state S as the root.

- Repeat up to K times:

  Pick a point q_{rand} in configuration space:

  - Sometimes q_{rand} is really random

  - Sometimes q_{rand} is the goal G

  – Find $q_{nearest}$, the closest node to q_{rand}

  - Add a new node q_{new} by extending $q_{nearest}$ some

    distance Δ toward q_{rand}.

  - If q_{new} is close enough to the goal G, return.

Image from
http://joonlecture.blogspot.com
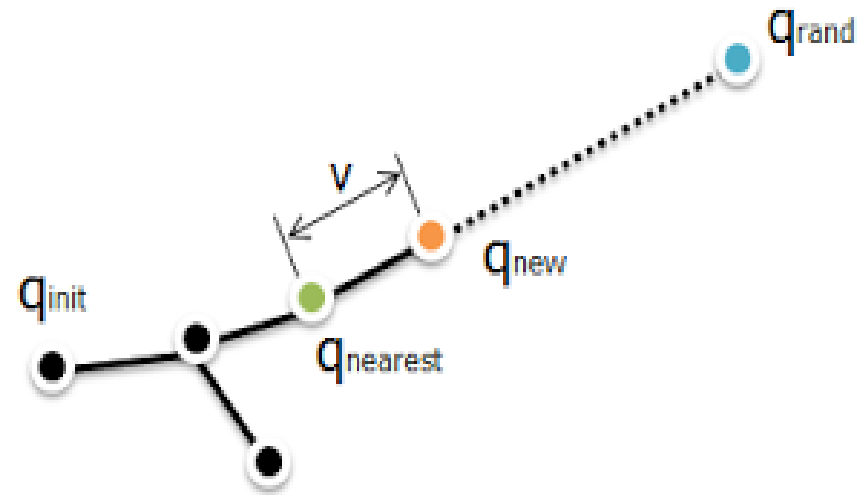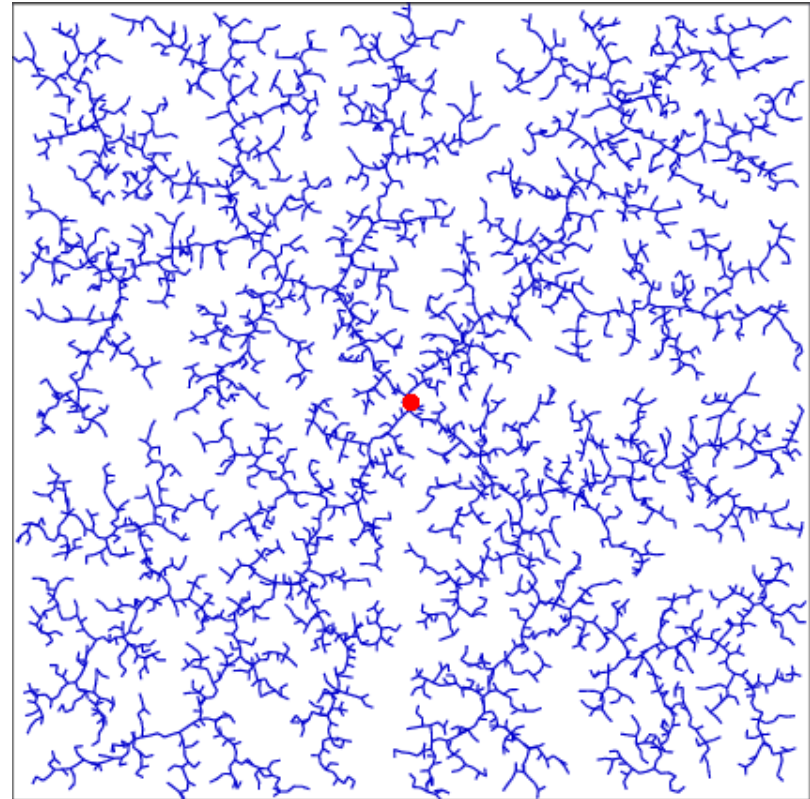/2011/02/improving-optimality-
of-rrt-rrt.html

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RRT Algorithm

- Rapidly samples the state space.

- Cannot get trapped in local minima.

- Works well in high-dimensional spaces.

- Does not generate smooth paths.

- Can't tell when no solution exists; only quits when it exceeds the iteration limit K.

http://msl.cs.uiuc.edu/rrt/treemovie.gif

RRTs for Arm Path Planning

- Each node encodes an arm configuration in joint space.

- Only add nodes that don't cause collisions (with self or obstacles).

- Alternately (i) extend the tree in random directions and (ii) move toward the goal.

Start configuration
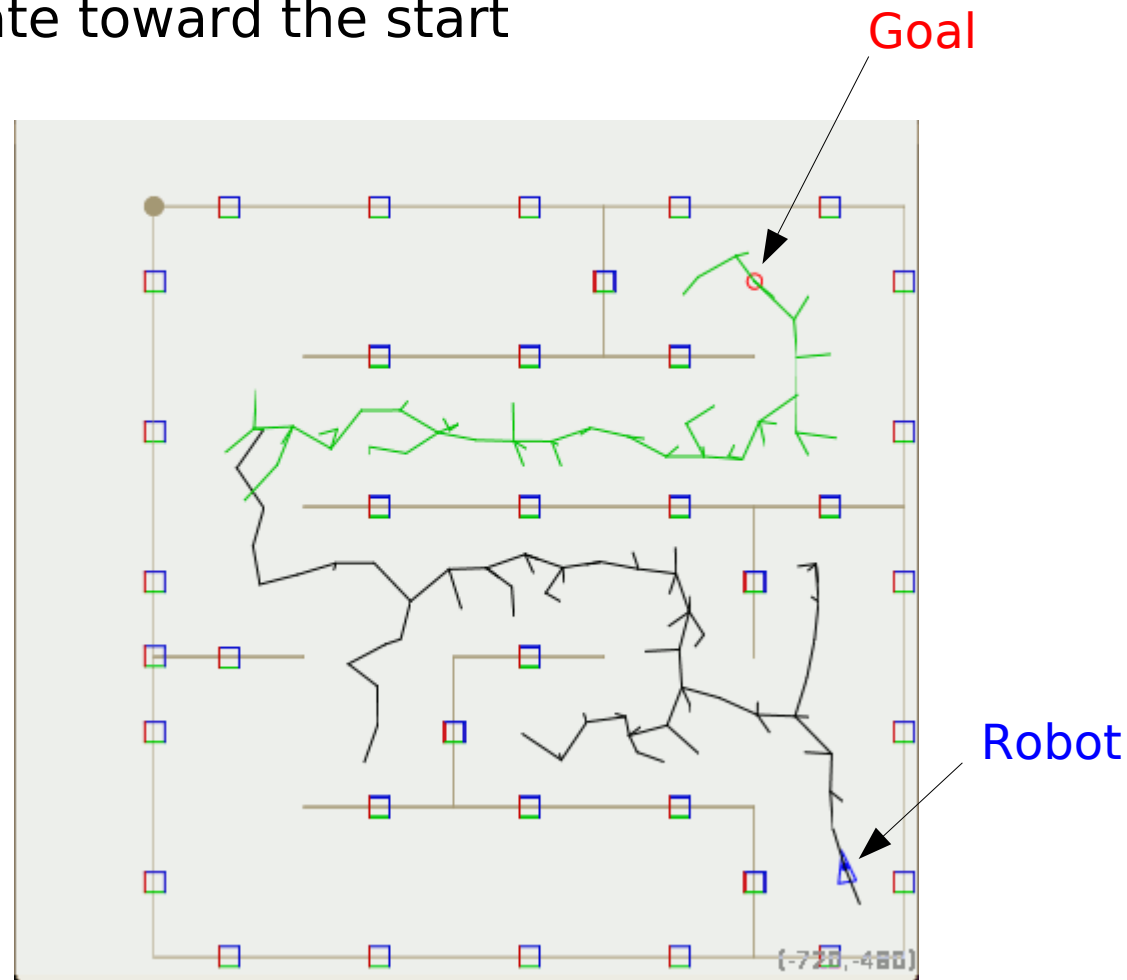
Slide courtesy of Glenn Nickens
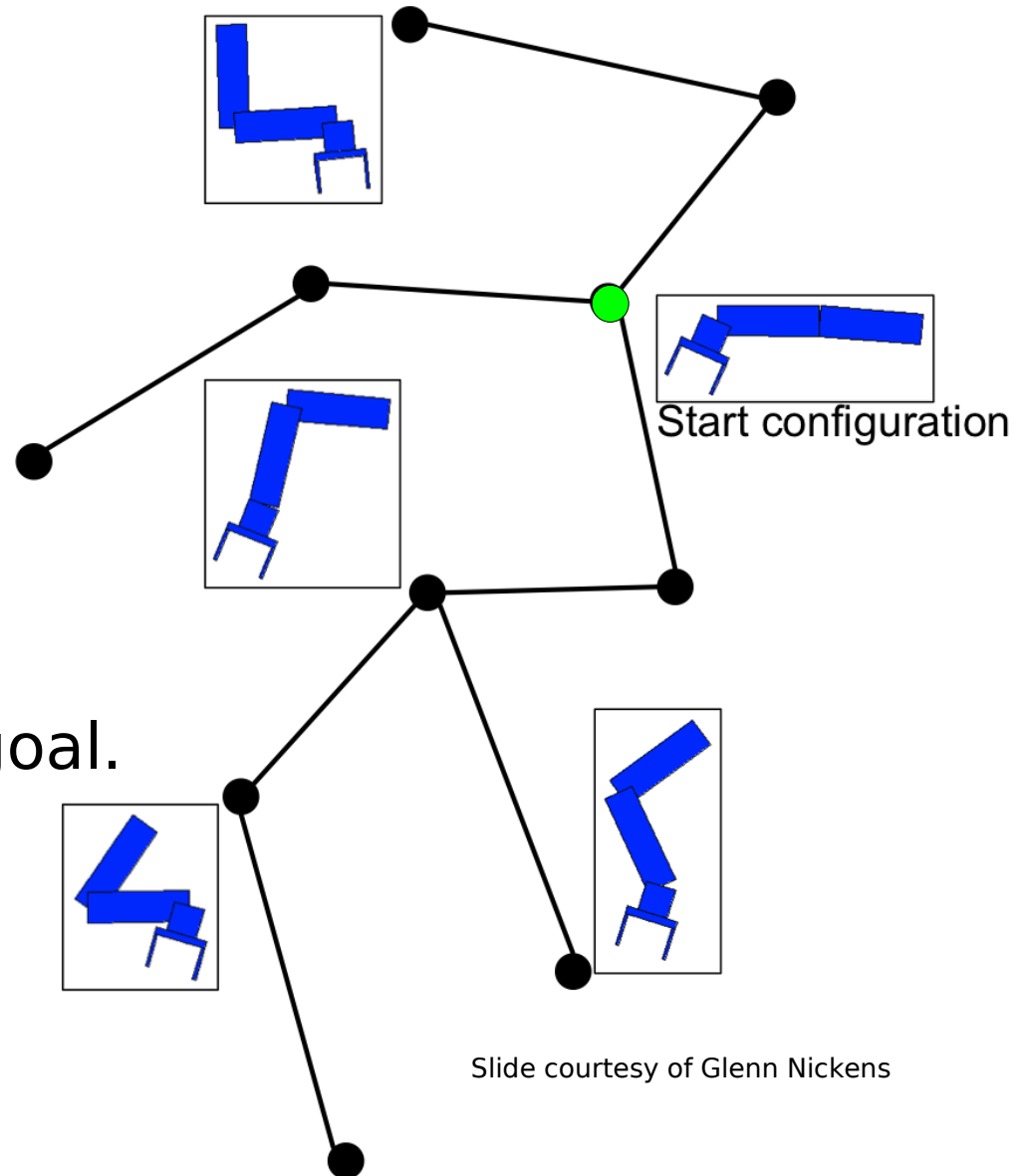
Implementation Notes

- Finding $q_{nearest}$, the nearest node in the tree to q_{rand}, is the most expensive part of the algorithm.

  - Use K-D trees to efficiently find $q_{nearest}$?

  - In practice, K-D trees are slower unless you have a huge number of nodes (several thousand).

- Why only go a distance Δ toward the goal state G? Why not go as far as we can, in steps of Δ?

  - With no obstacles, this reaches the goal very quickly, but random search will get there nearly as quickly as we keep extending the nearest node to the goal.

  - But when obstacles are present, this can waste time filling out branches that will ultimately fail.

  - Generating lots of extra nodes bloats the tree, which slows down the algorithm.
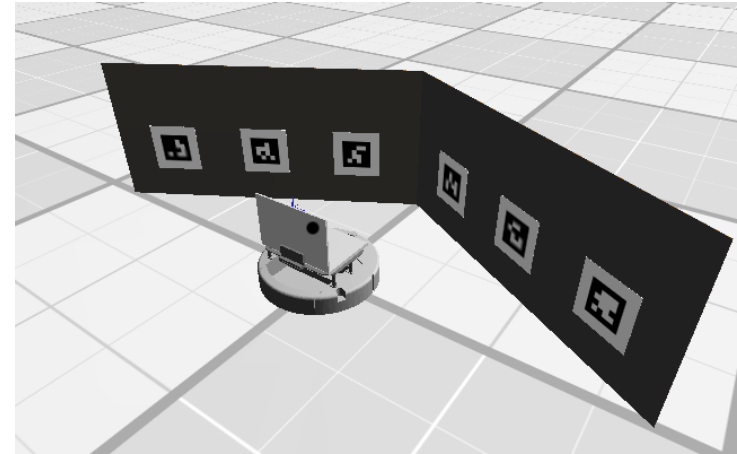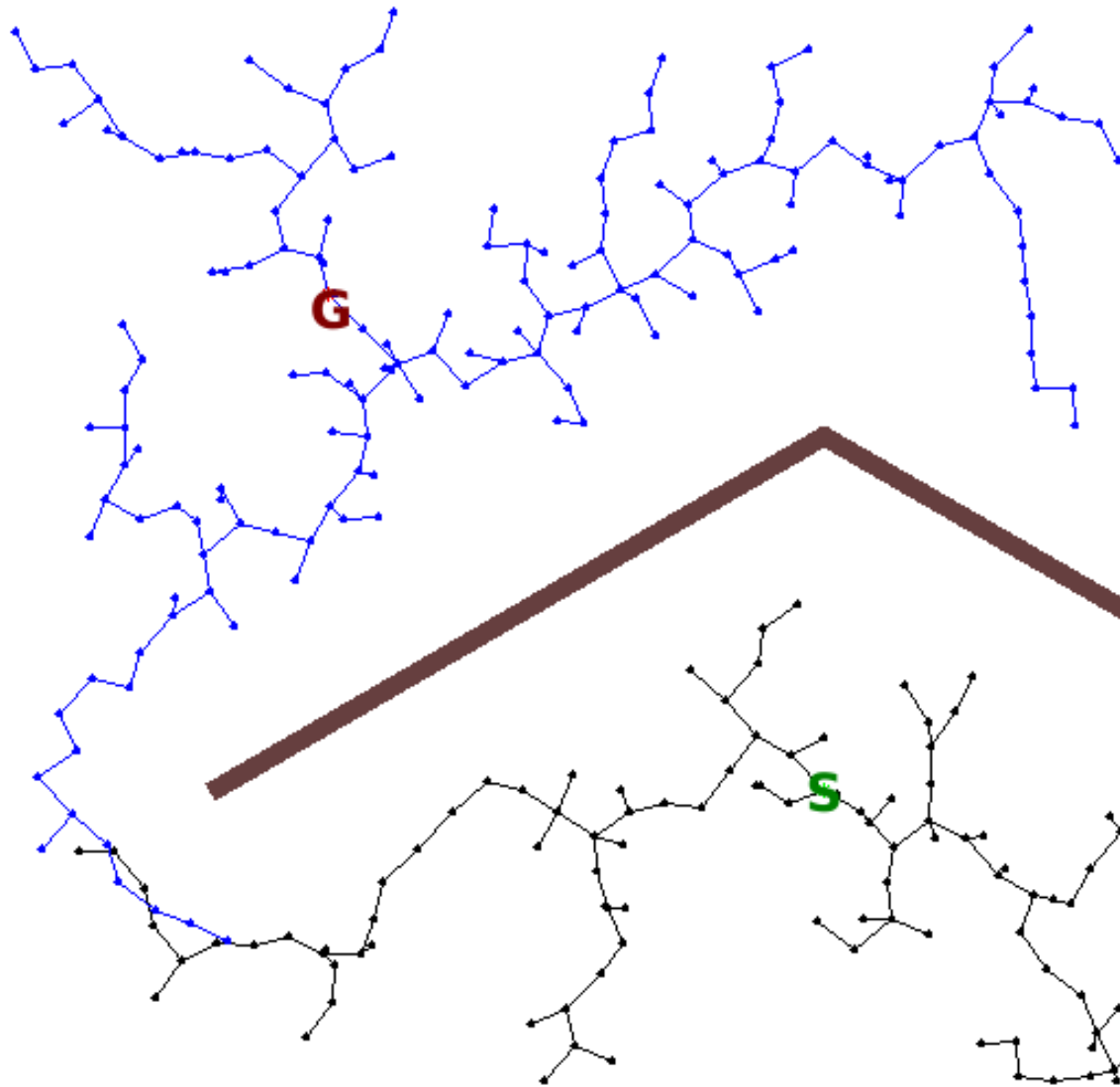
RRT-Connect Algorithm

- Variant of RRT that grows two trees:
    - one from the start state toward the goal
    - one from the goal state toward the start

- When the two trees connect, a solution has been found.
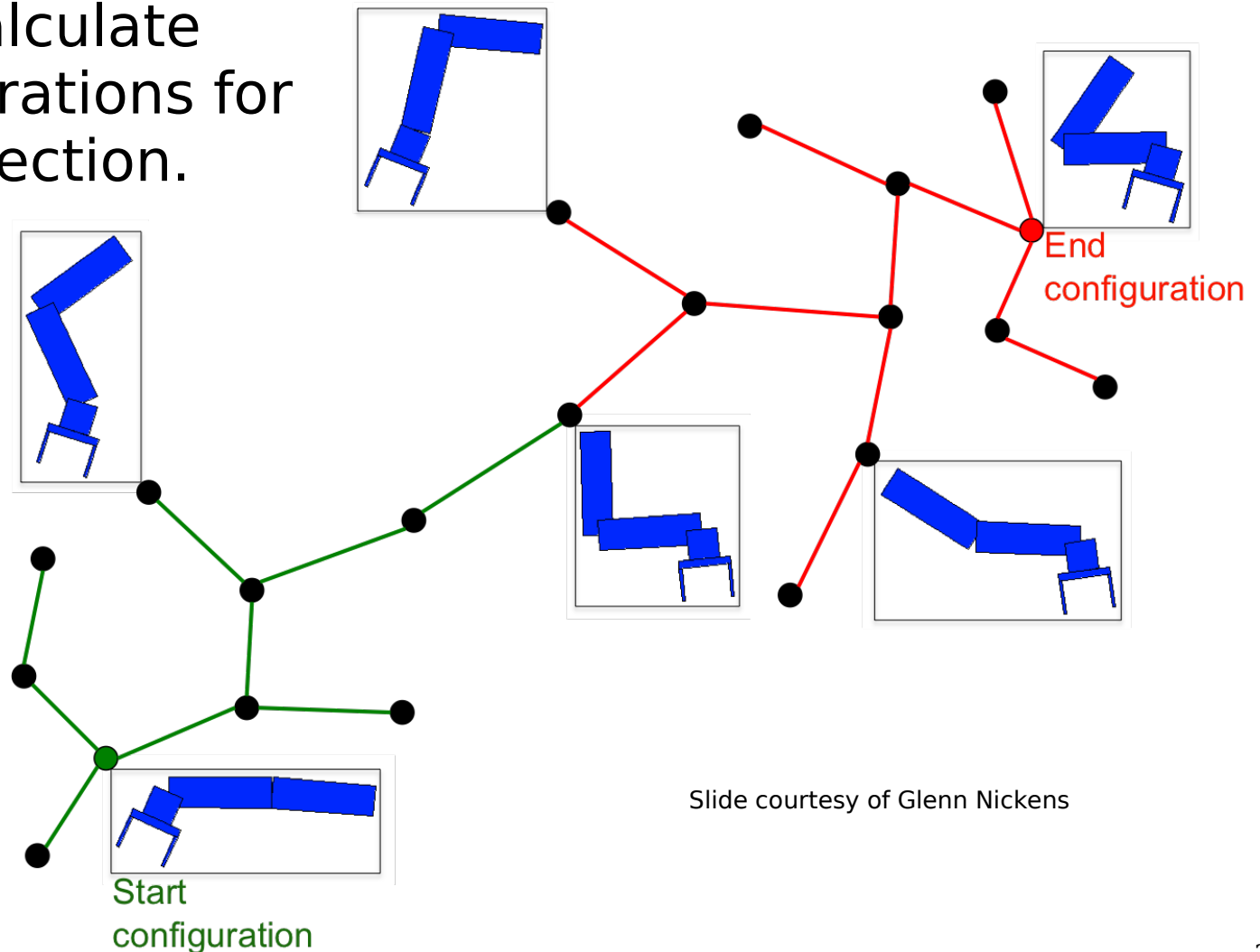
- Not guaranteed to be better than RRT, but often helps.
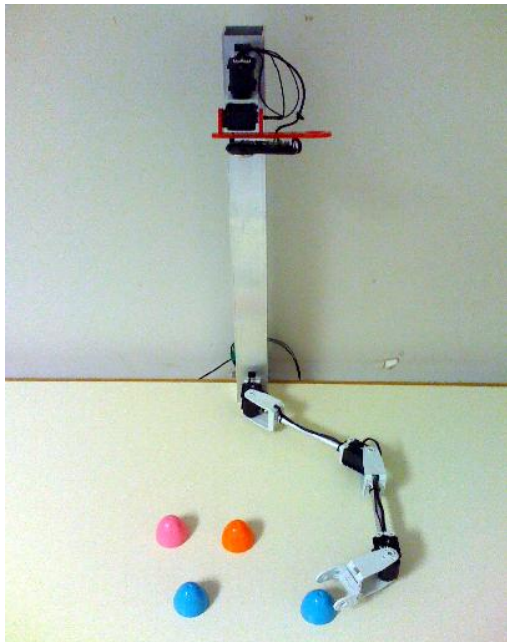

Goal

Robot

RRTs in An Open Field

RRT-Connect For Arms

- Use IK to calculate the goal configuration.

- Use FK to calculate arm configurations for collision detection.

End configuration

Start configuration

Slide courtesy of Glenn Nickens

Collision Detection

- Represent the robot and the obstacles as **convex polygons**.

- In 2D, use the Separating Axis Theorem to check for collisions.

  - Easy to code

  - Fast to compute

- In 3D, things get more complex.

  - Could use the GJK (Gilbert-Johnson-Keerthi) algorithm, used in many physics engines for video games.

Algorithm to Apply the SAT

- For every edge of polygon A and of polygon B:

    - Project all the vertices onto the line normal to that edge.

    - Calculate the min and max coordinates for each polygon

    - If minA < minB and maxA > minB OR
        if minB < minA and maxB > minA
            then the polygons collide.

- If you find any edge projection in which the ranges don't overlap, the polygons do not collide.

# Separating Axis Theorem

Separating
line

Separating
axis

b

Max b

Min b

a

Max a

Min a
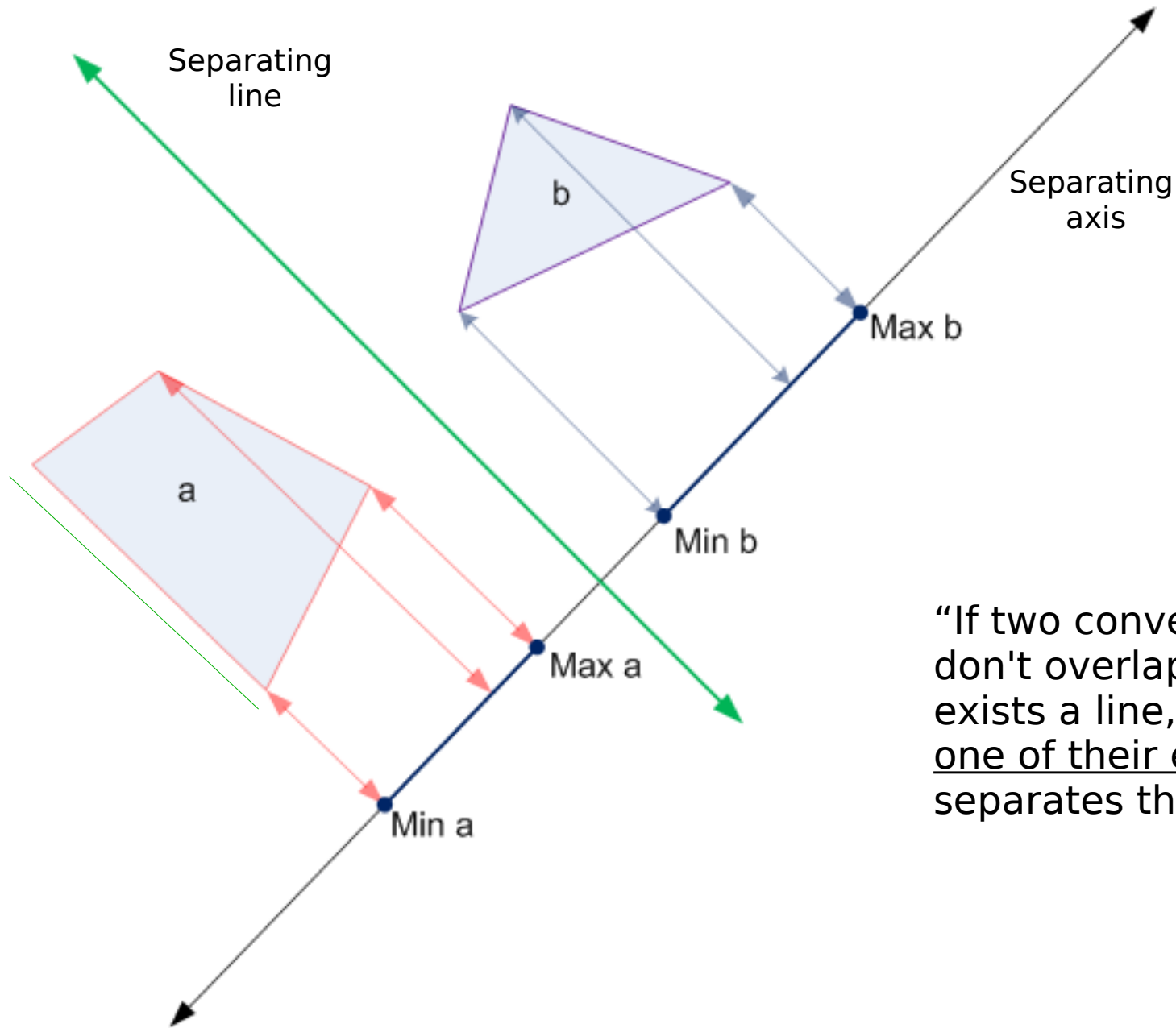
"If two convex polygons
don't overlap, then there
exists a line, parallel to
<u>one of their edges</u> that
separates them."

Separating Axis Theorem
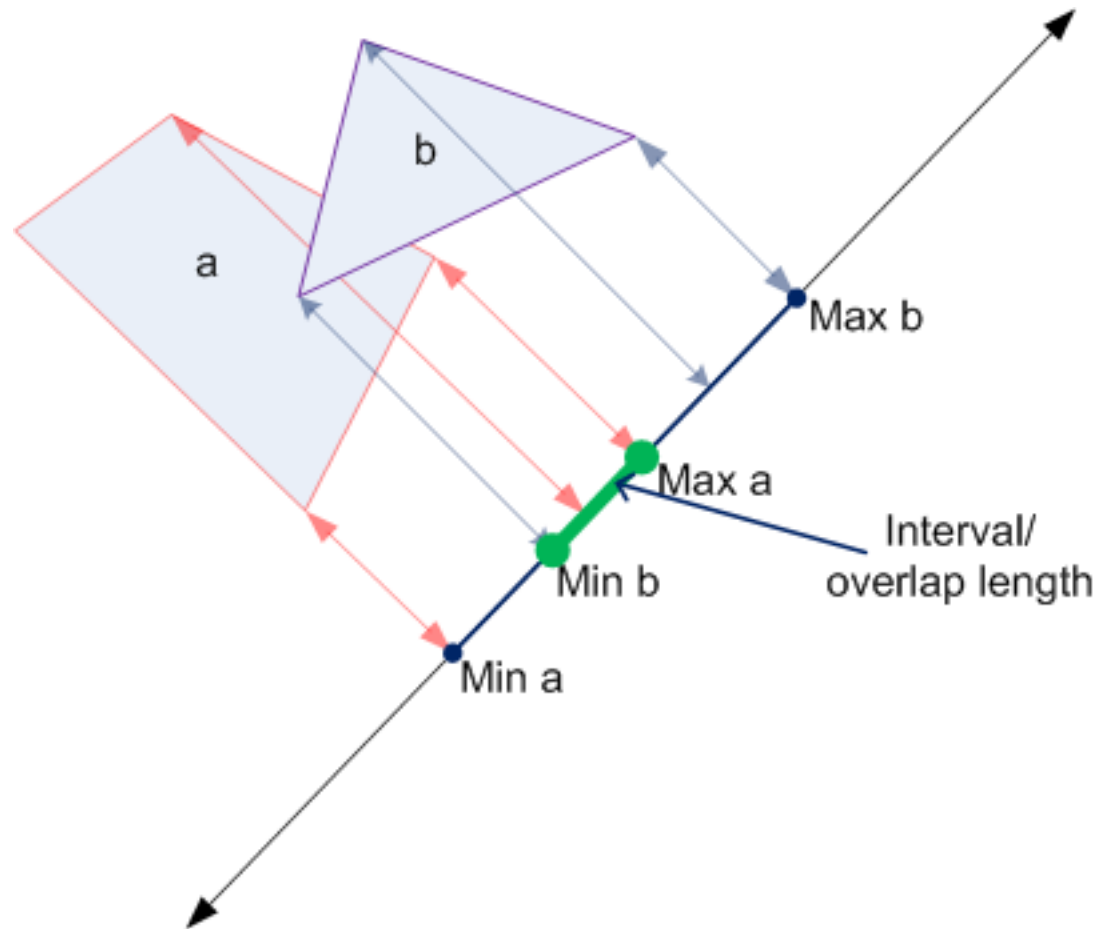
Arm Collision Detection

- Represent each link as a separate polygon.

- Check for:

  – Self-collisions other than link *n* with link *n+1*

 – Collisions of a link with an obstacle
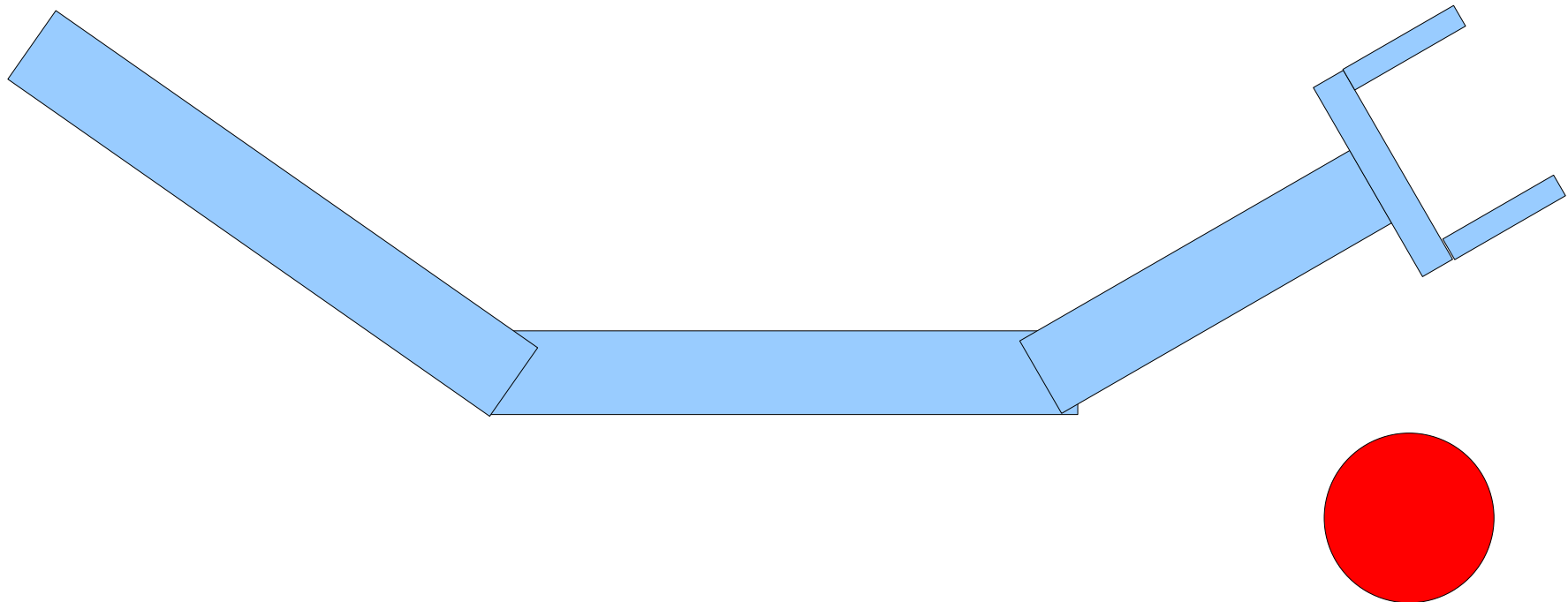
Path Smoothing

- The random component of RRT-Connect search often results in a jerky and meandering solution.

- Solution: apply a path smoothing algorithm.

- Repeat N times:

  - Pick two points on the path at random

  - See if we can linearly interpolate between those points without collisions.

  - If so, then snip out that segment of the path.
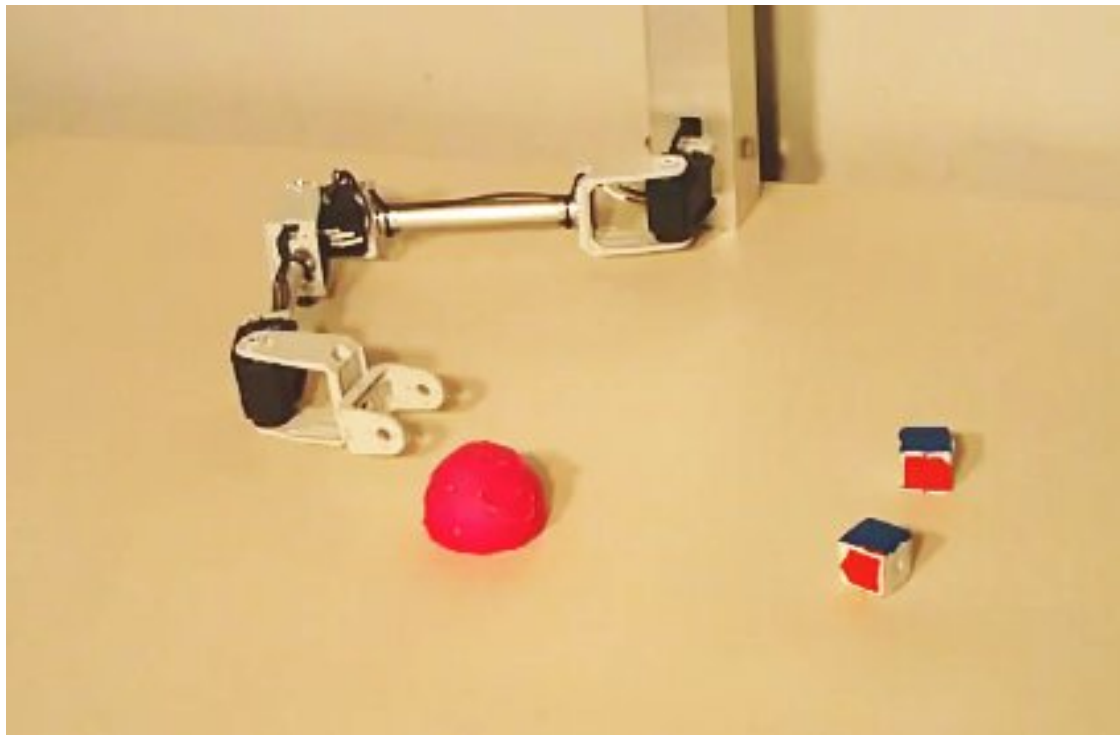
Smoothing An Arm Trajectory

- Start state
- Intermed. states
- End state

Original
Path

Obstacle

Smoothed
Path

Slide courtesy of Glenn Nickens

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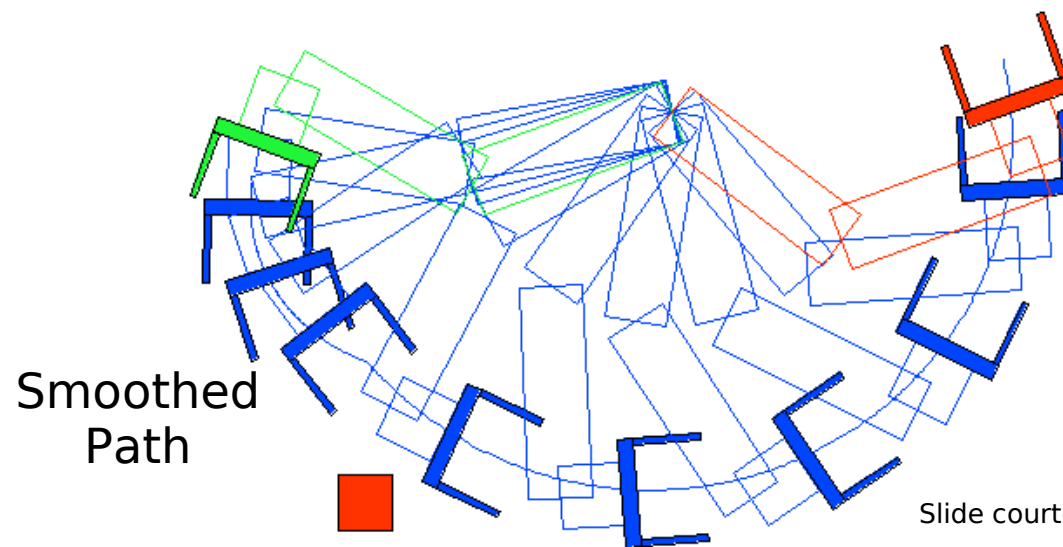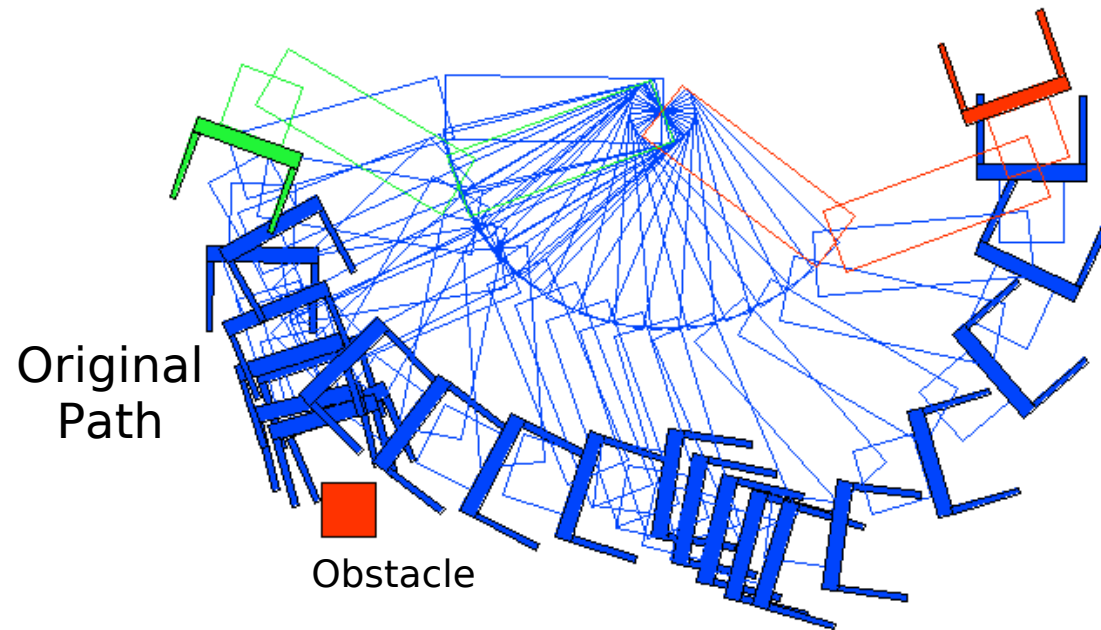
Path Planning With Constraints

- With no closeable fingers, arm motion is constrained to be within about 60º of finger direction or we'll lose the object.

(video)

http://www.youtube.com/watch?v=9oDQ754YVoc

Implementing Constraints

- Each time we generate a new state q_{new}:

    - Check to see if q_{new} obeys the constraint.

    - For finger motion constraint, check if the direction of motion from parent state $q_{nearest}$ to new state q_{new} is within 60° of the finger direction.

- What if q_{new} doesn't obey the constraint?

    - Reject it and pick a new q_{rand} from which we'll generate a new q_{new}.

    - Or try to "fix" q_{new} by perturbing its value slightly so as to satisfy the constraint.
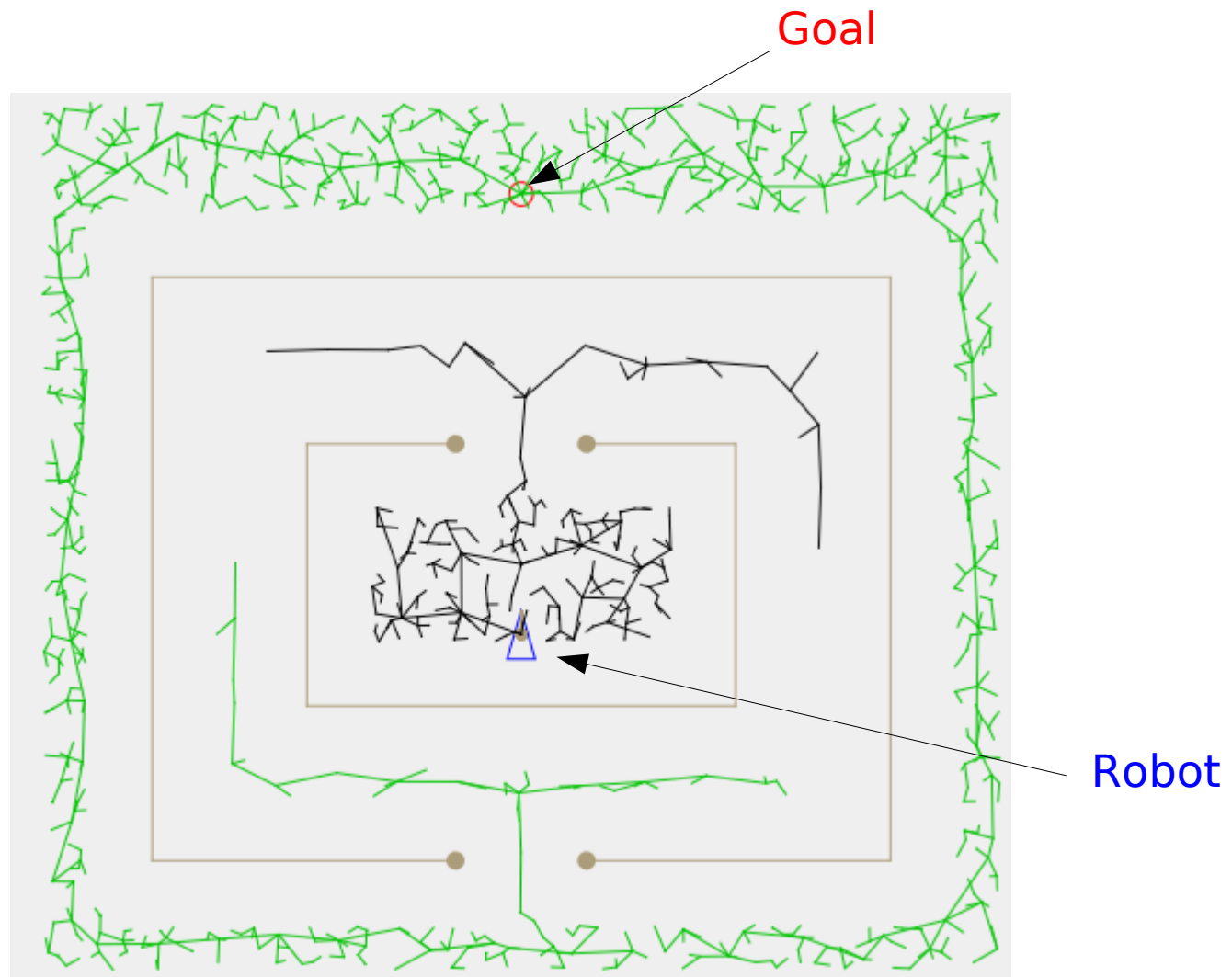
Path Planning Failure

RRT path planning can legitimately fail if:

- There is no route to the goal due to obstacles blocking every path from start to goal.

- The paths to the goal don't lie entirely within the allowed world bounds (world map too small).
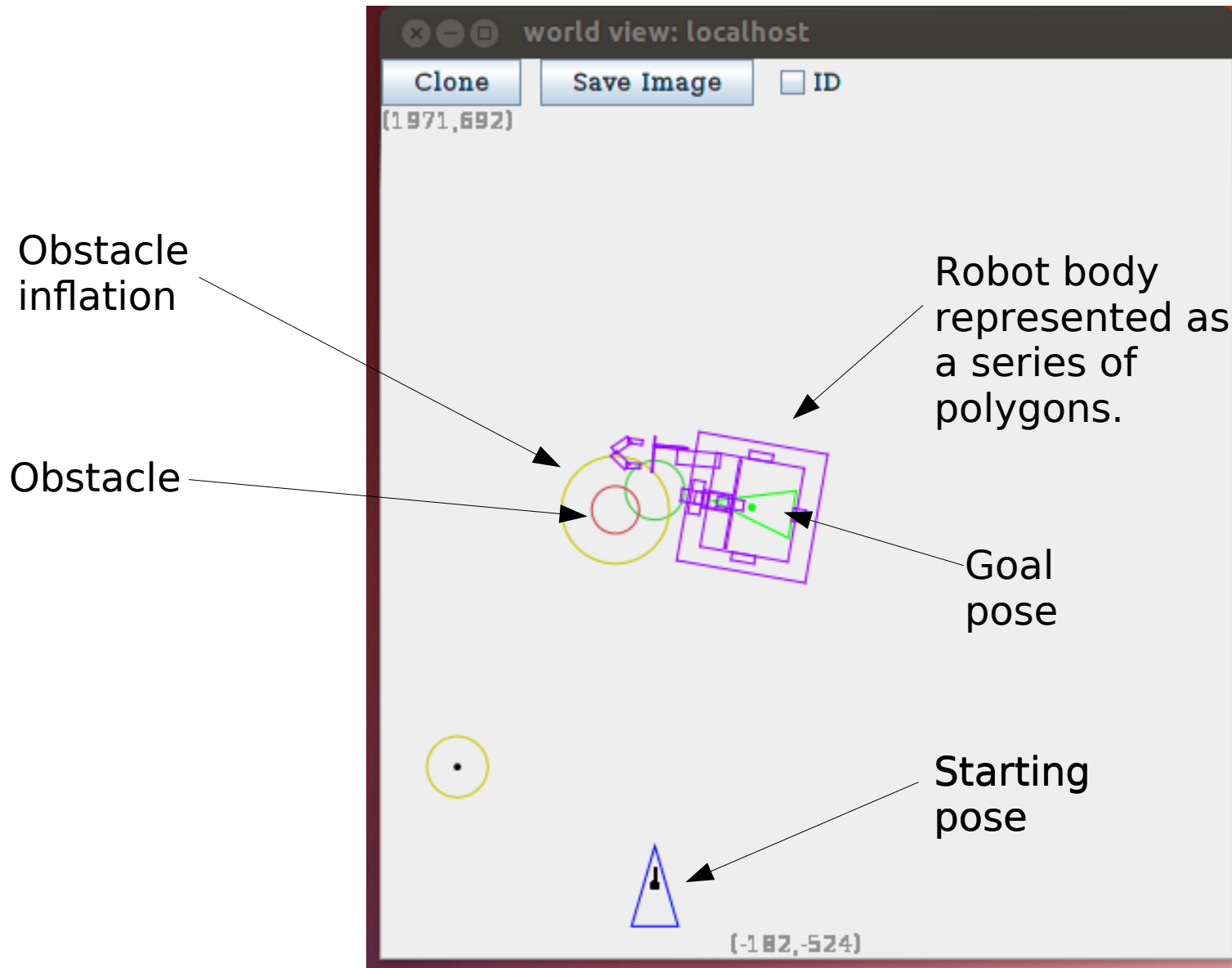
But it can also fail if:

- The iteration limit was set too low.

- The start state is already in collision with something.

- The goal state is in collision with something.

Running Out of Iterations

Goal

Robot

Path Planning Failure: Goal State Is In Collision
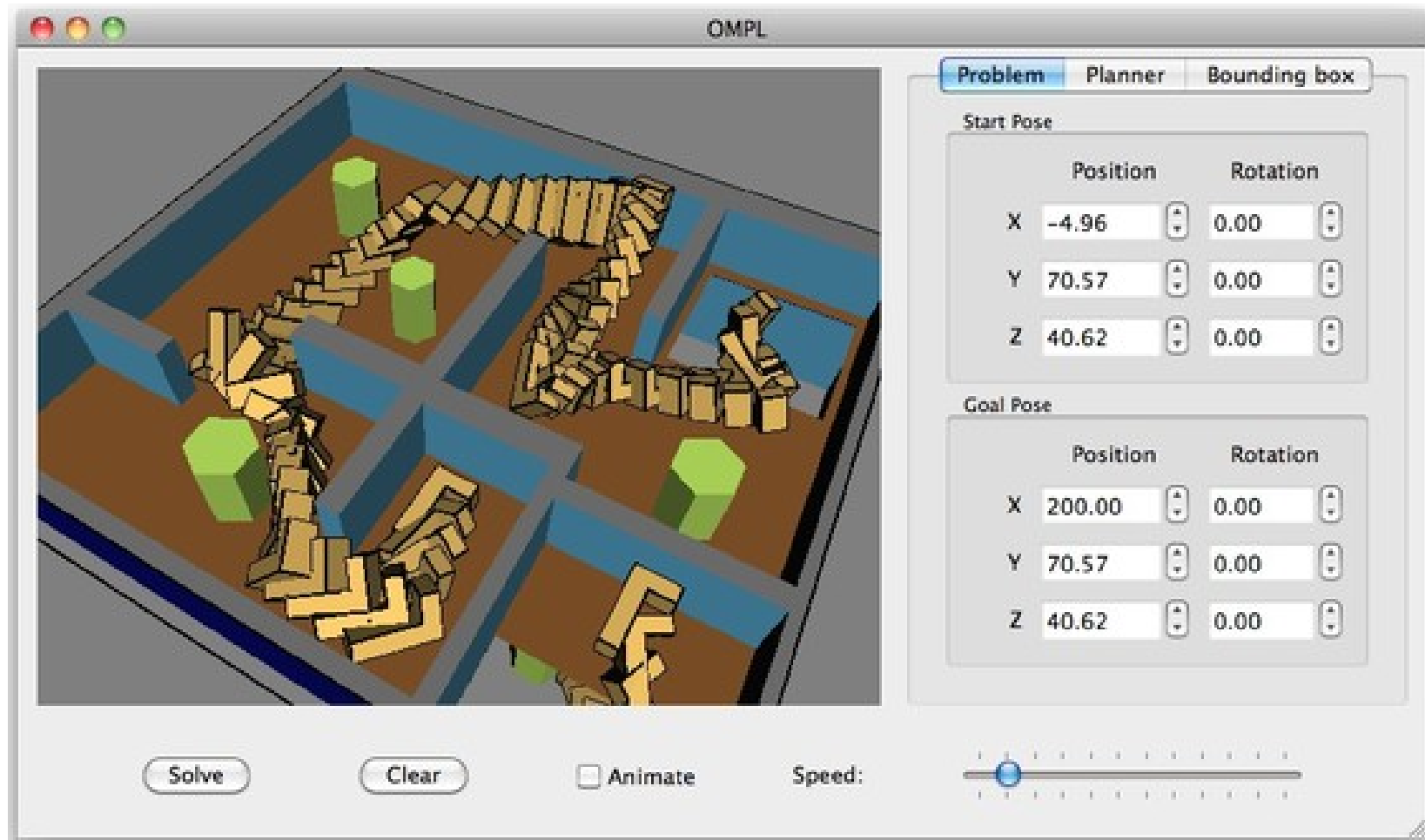
Full 3D Path Planning:
The Piano Movers Problem

Open Motion Planning Library:
http://ompl.kavrakilab.org

The Pilot

- Navigation utility defined in aim_fsm/pilot.fsm

- How to go from A to B:
    - Generate obstacle list from current world map.
    - Use RRT-Connect to plan a path from A to B?
        - Good in open spaces; has trouble with doorways.
    - Formulate a navigation plan to follow the path.
        - Straight segments
        - Turns
        - Arcs
        - Landmark checks
    - Execute the navigation plan, correcting as necessary.
   - Report success or failure.

PilotToPose Node

- State node for invoking the Pilot.

- Tell it where you want to go, and (optionally) the desired heading at the destination.

- Use a heading of NaN if you don't care.

- =PILOT=> transition can check for errors.

```
go: PilotToPose(Pose(500, 0, 0, theta=90*(pi/180)))
go =C=> Say("Success")
go =PILOT(StartCollides)=> Say("Start collides!")
```

Path Viewer

`PilotToPose(Pose(300, 0, 0, theta=90*(pi/180))))`
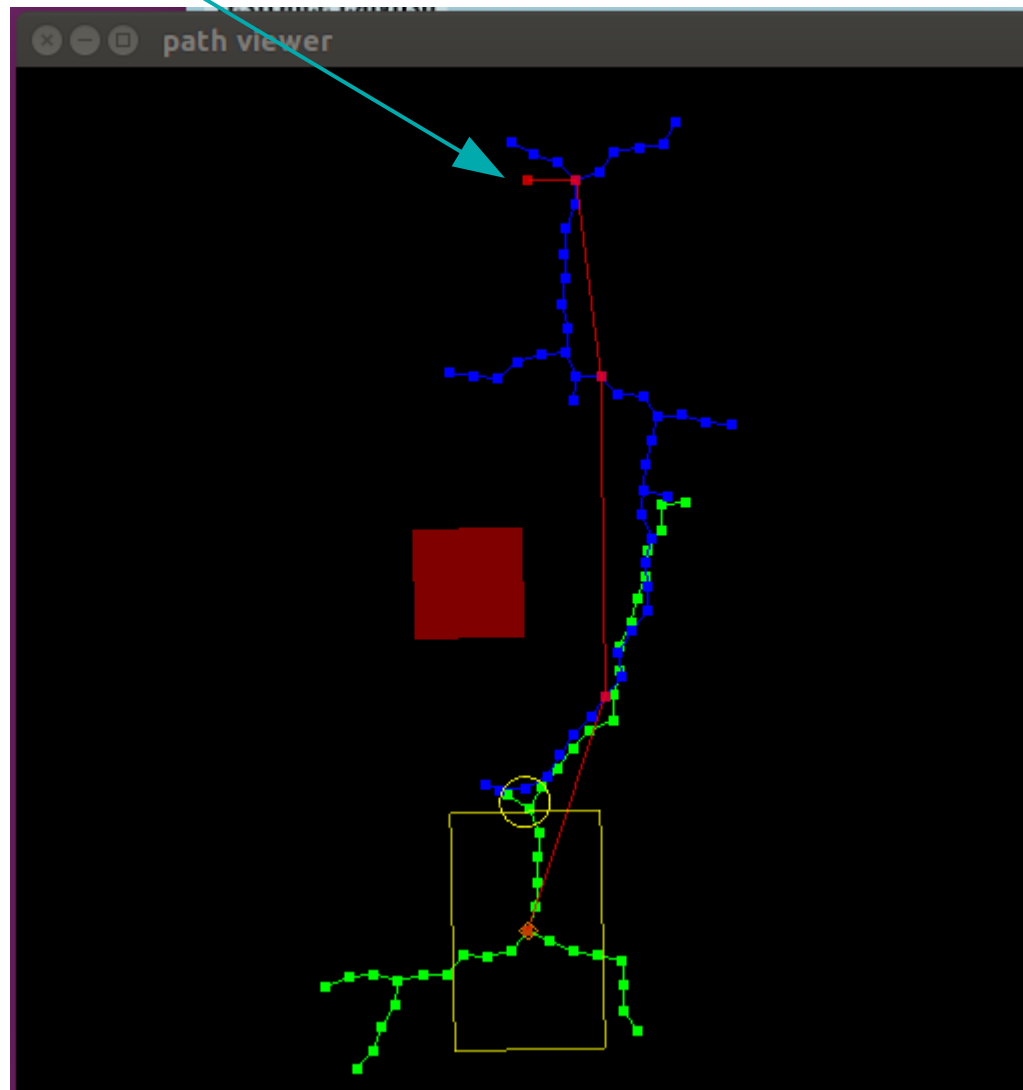
Hybrid Path-Planner

- vex-aim-tools will use a hybrid path planner.

- Check for StartCollides condition and use RRT to find a maneuver that disengages from the obstacle, e.g., move away from a wall.

- Wavefront algorithm finds a route to the goal using large obstacle inflation. Easily goes through doorways.

- RRT post-processing:

  - Check for collisions using actual robot shape and less obstacle inflation

  - Generate a condensed path with fewer steps

- Check for doorway crossing and insert "doorpass" steps in the navigation plan.