Manipulation By Pushing

15-494 Cognitive Robotics

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Introduction

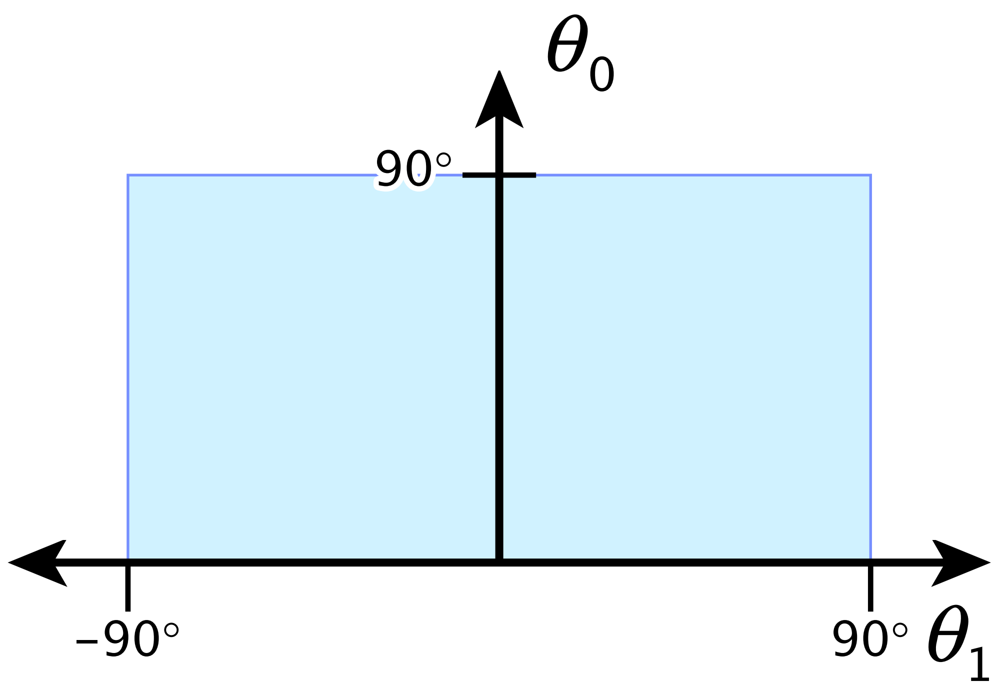
- Affordances are where we want to *be*
- Kinematics are where we *are*
- How do we get from basic kinematics to actually *doing* something?

Introduction

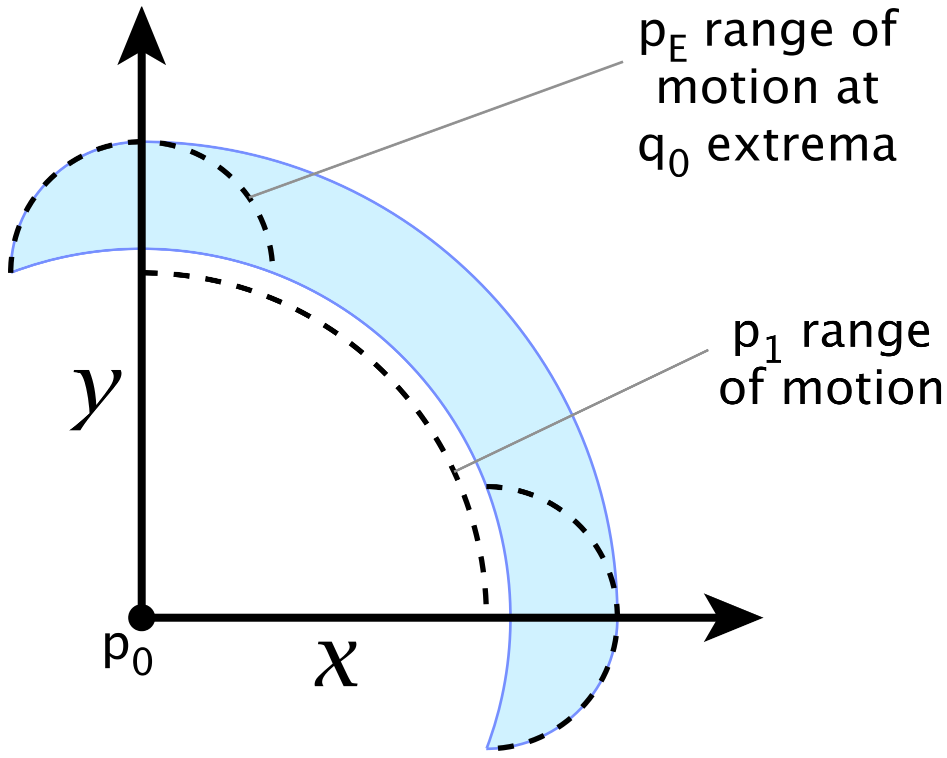
- How do we get from basic kinematics to actually *doing* something?
  - Configuration Space vs. Work Space
  - Constraints
    - Form Closure vs. Force Closure
    - Grasp Analysis (Reuleaux's Method)
  - Path Planning
    - Cspace, visibility graph, best first, RRT

Configuration Space vs. Work Space

- Consider a 2-link arm, with joint constraints: $0° < \theta_0 < 90°$, $-90° < \theta_1 < 90°$



Configuration Space: robot's internal state space (e.g. joint angles)



Work Space: set of all possible end-effector positions

Constraints

- Constraints can be your friend!
  - Upside: Use the environment and the object itself to your advantage.
  - Downside: Requires planning and *accurate* modeling
- Example: Part Orientation
  - Can position/orient an ‘L’ shaped part with unknown initial configuration using nothing more than an actuated tray — no sensors!

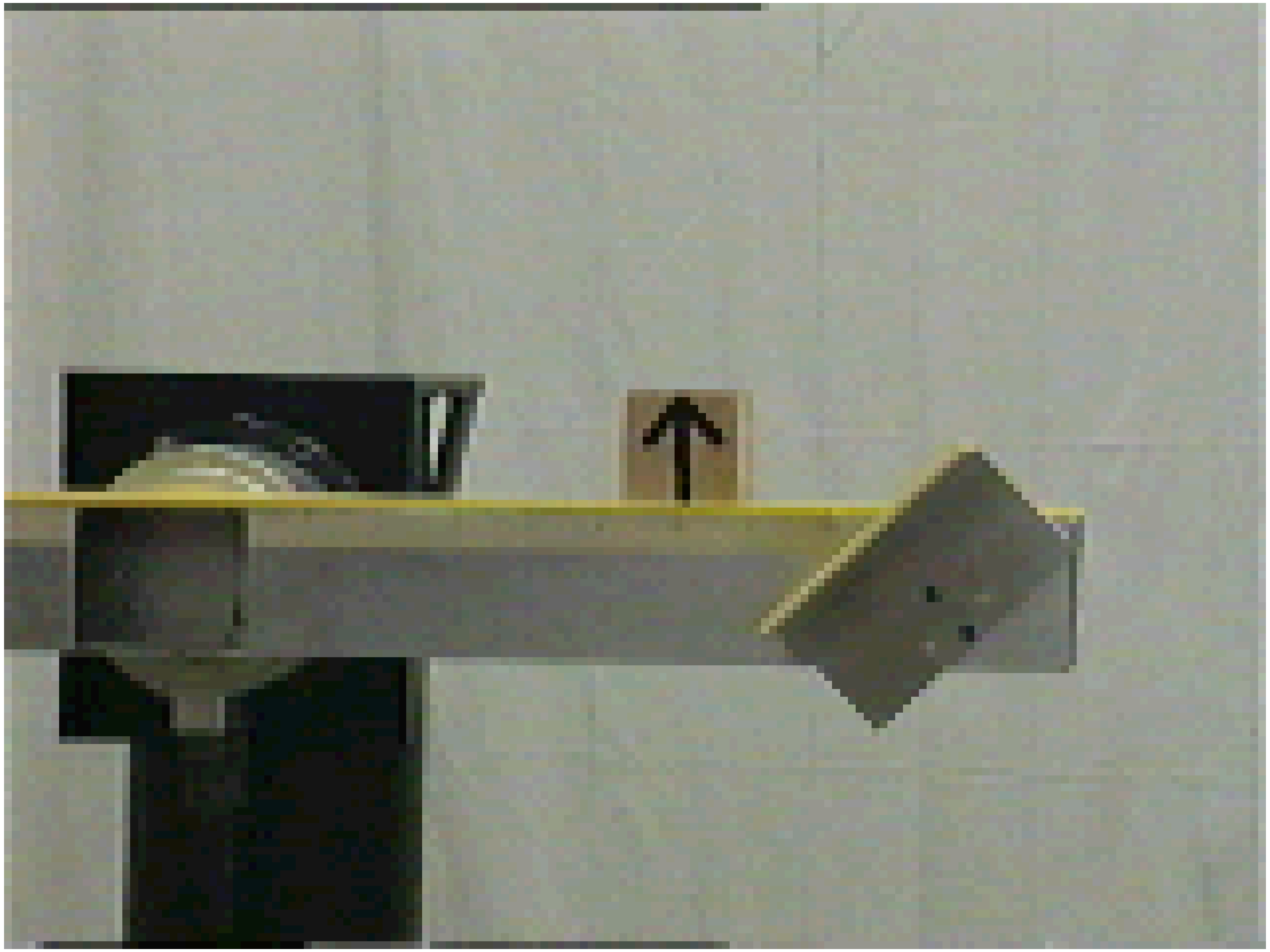
Constraints Are Your Friend

- Example: Part Orientation

Fujimori, T., *Development of Flexible Assembly System "SMART"*
Video of Sony SMART Cell demo system by Wes Huang
CMU Manipulation Lab

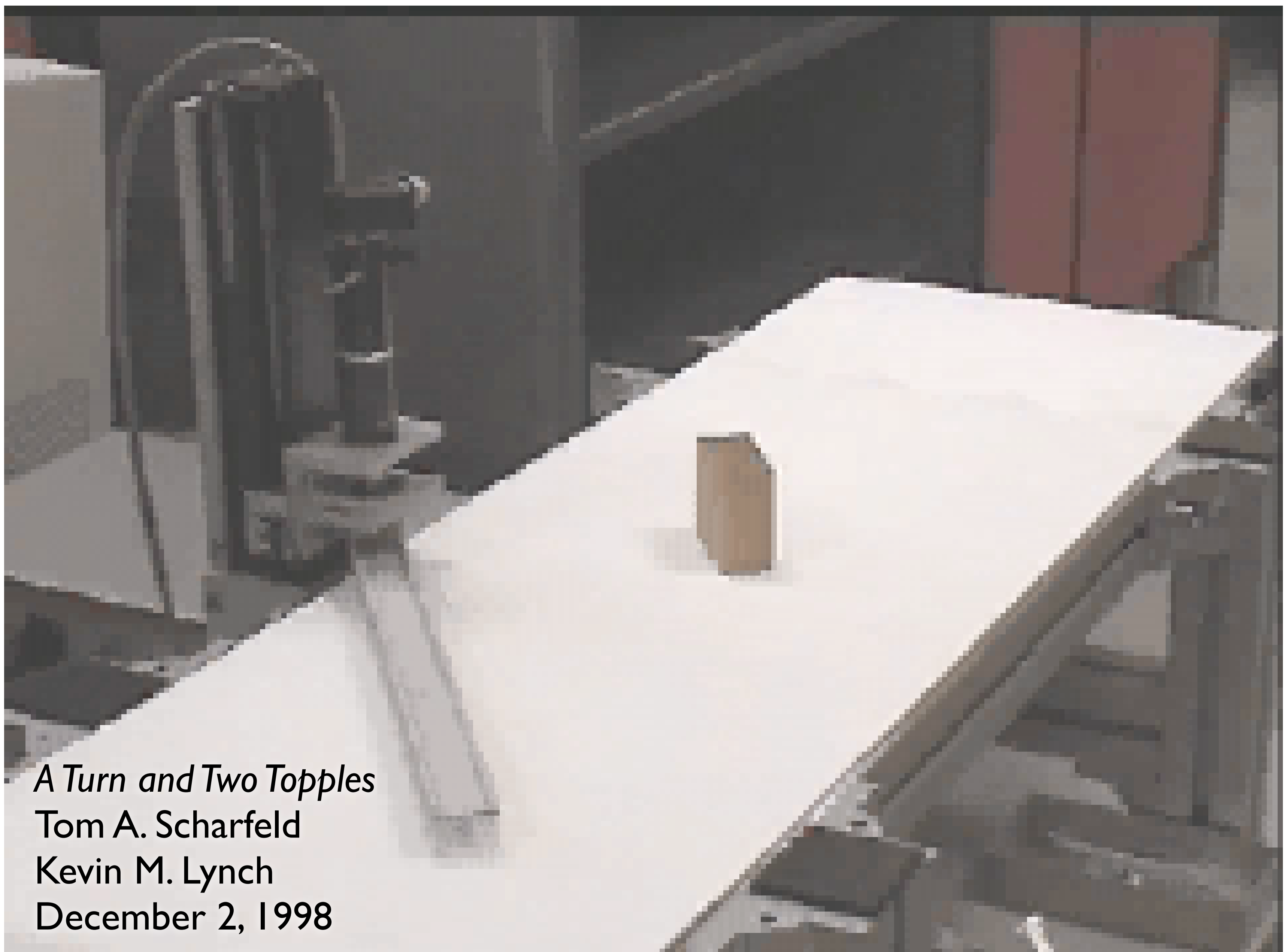
Constraints Are Your Friend

- Example: Throwing (Kevin Lynch)



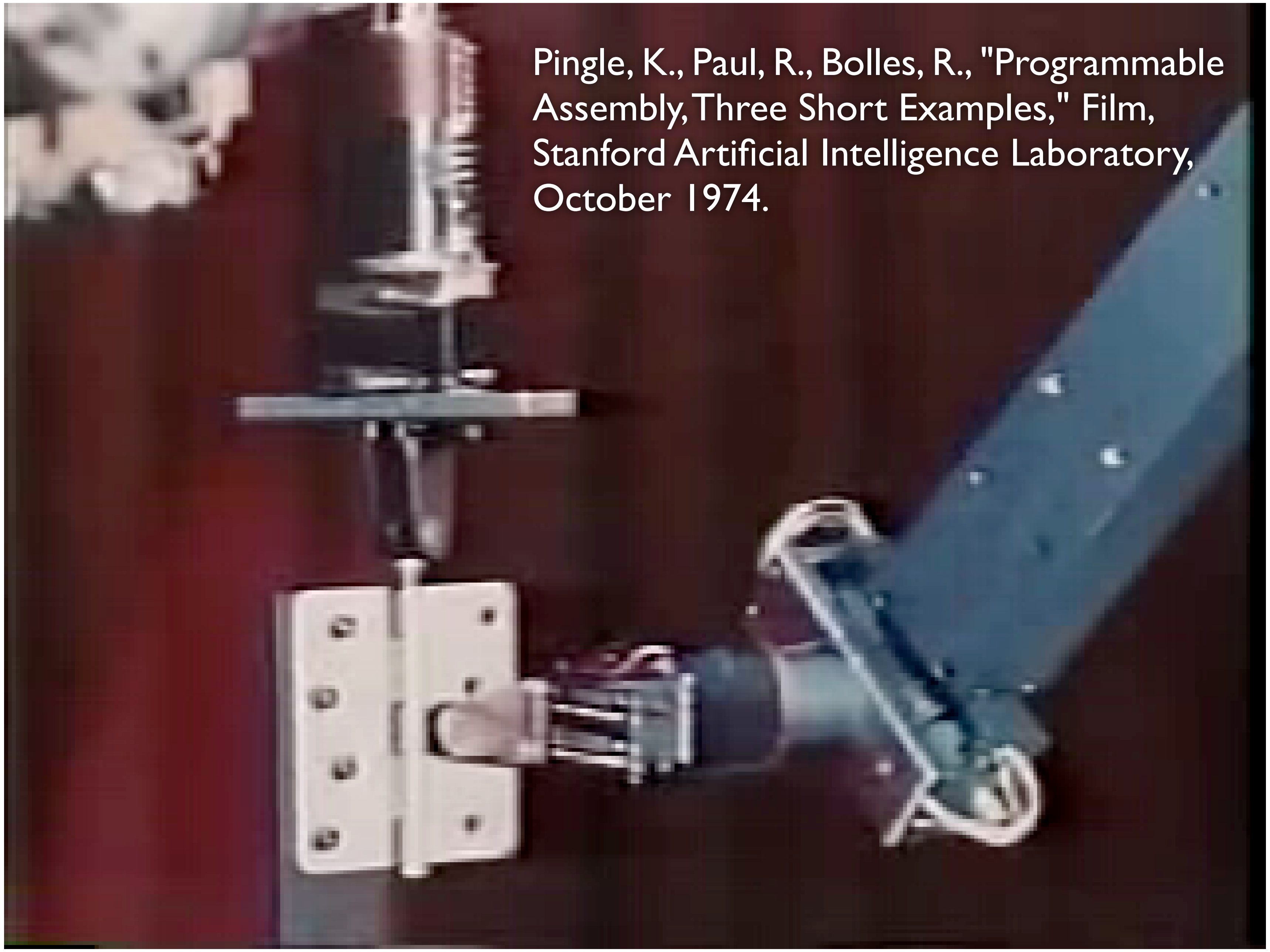
Constraints Are Your Friend

- 2 DOF Arm over a conveyor belt (2JOC)



Constraints Are Your Friend

- Example: Hinge Assembly



Constraint Taxonomy

- Bilateral - expressed by equality (e.g. $y = 0$)
- Unilateral - expressed by inequality (e.g. $y > 0$)

- Scleronomic - independent of time (static)
- Rheonomic - changes over time (e.g. $\theta = 2\pi t$)

- Holonomic - all constraints are independent of rate of change and bilateral (direct mapping between configuration space and work space)

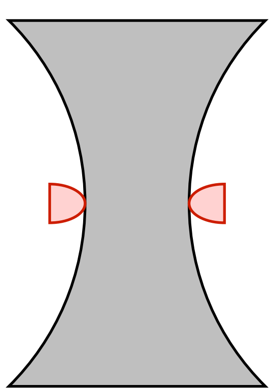
Holonomic vs. Non-Holonomic

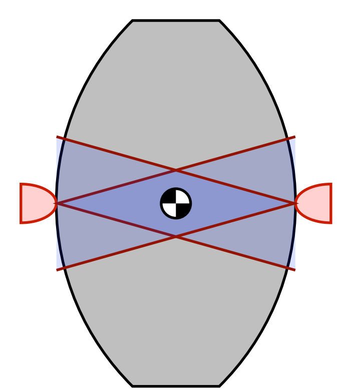
- Holonomic: robotic arms, unsteered mobile robots, omni-directional mobile robots
    - can define configuration space such that returning to a configuration point implies returning to consistent point in work space
- Non-Holonomic: commonly, mobile robots with constraints on their instantaneous motion, e.g. unicycles, steered carts (Ackerman steering) can't go sideways

Grasping

- What does it mean to "hold" something?
  - *Form closure*: object is "secure" — can't move without moving a contact point
  - *Force closure*: can apply any desired force
- Not necessarily the same thing — depends on your friction model (next lecture)

No friction:
Form closure, but no force closure

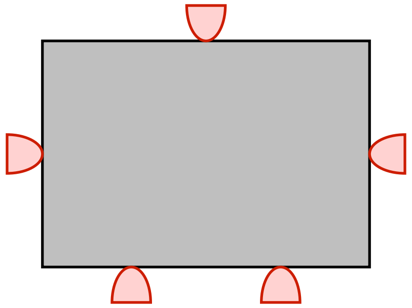




With friction:
Force closure, but no form closure

Grasping

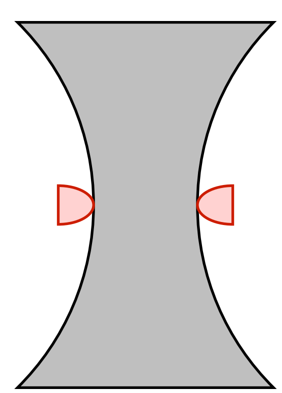
- Form closure is defined in increasing *orders*: position, velocity, acceleration, etc.
- Force closure does not have orders (you have it or you don't)
- Frictionless force closure equates to *first-order* (positional) form closure



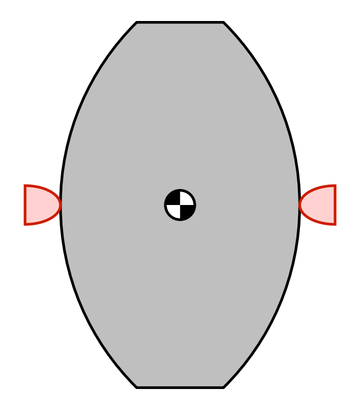
Example grasp with both force closure and first-order form closure, regardless of frictional model

Grasping

- Original examples do not have force closure
- Left figure can be moved infinitesimally up or down, although cannot be in motion vertically (so it has second-order form closure)



With no friction, neither example has force closure nor <u>first-order</u> form closure



Grasping

- What does it mean to "hold" something?
  - *Form closure*: object is "secure" — can't move without moving a contact point
  - *Force closure*: can apply any desired force
  - *Equilibrium*: can resist environmental forces (gravity)
  - *Stablity*: how much variance from the environment can be tolerated and still maintain equilibrium

Taxonomy of Contacts

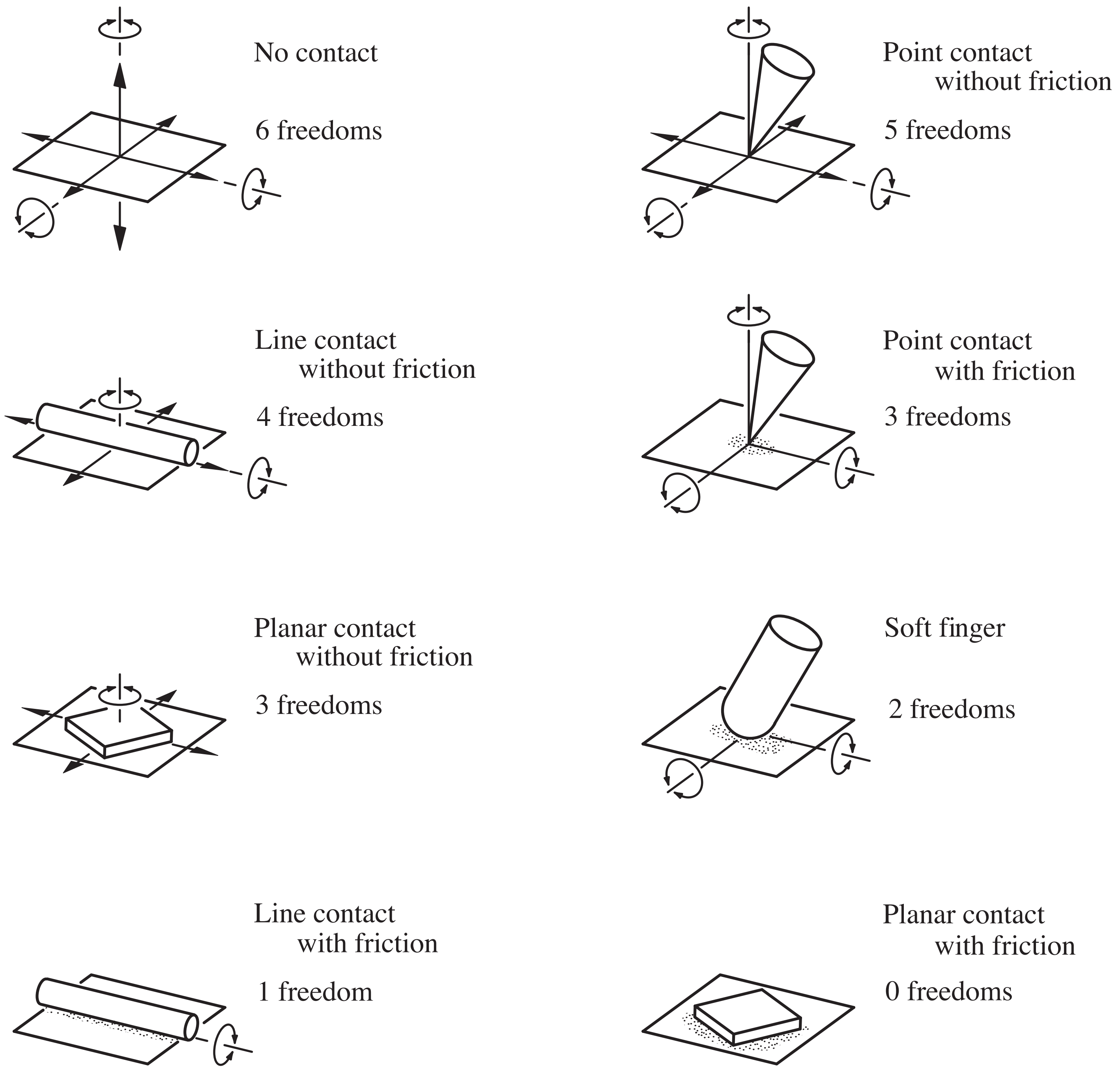
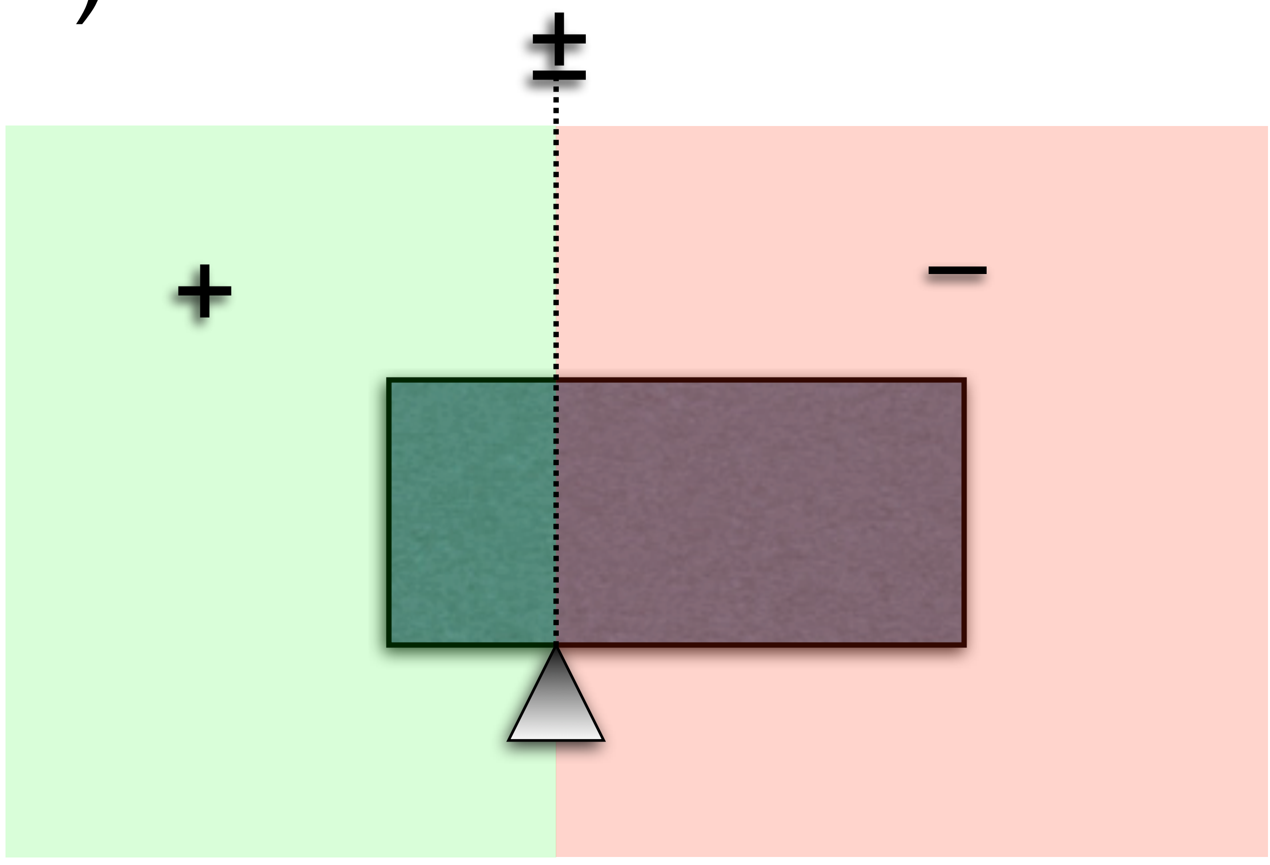


Figure 4.8 - Mason, Mechanics Of Robotic Manipulation

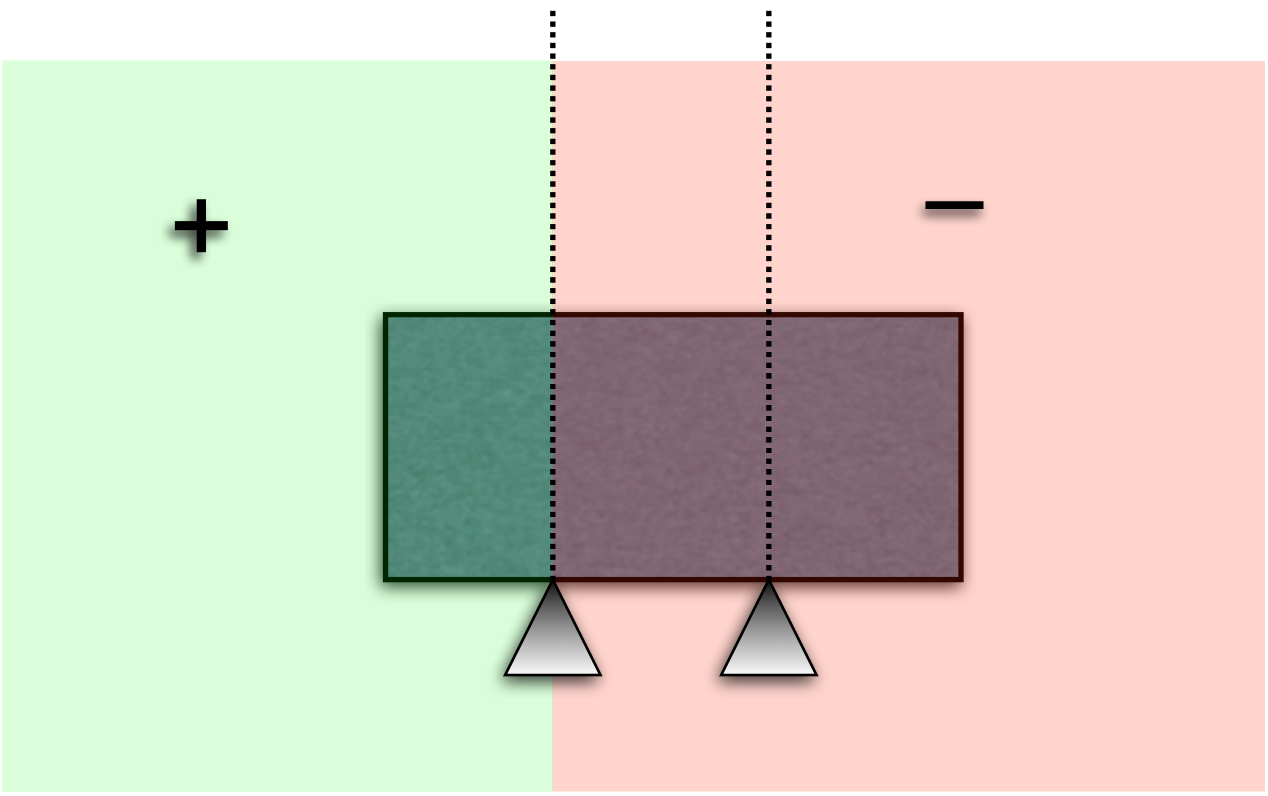
Grasp Analysis: Reuleaux's Method

- For each constraint, divide the plane into areas which can hold positive or negative centers of rotation (IC's - instantaneous centers)



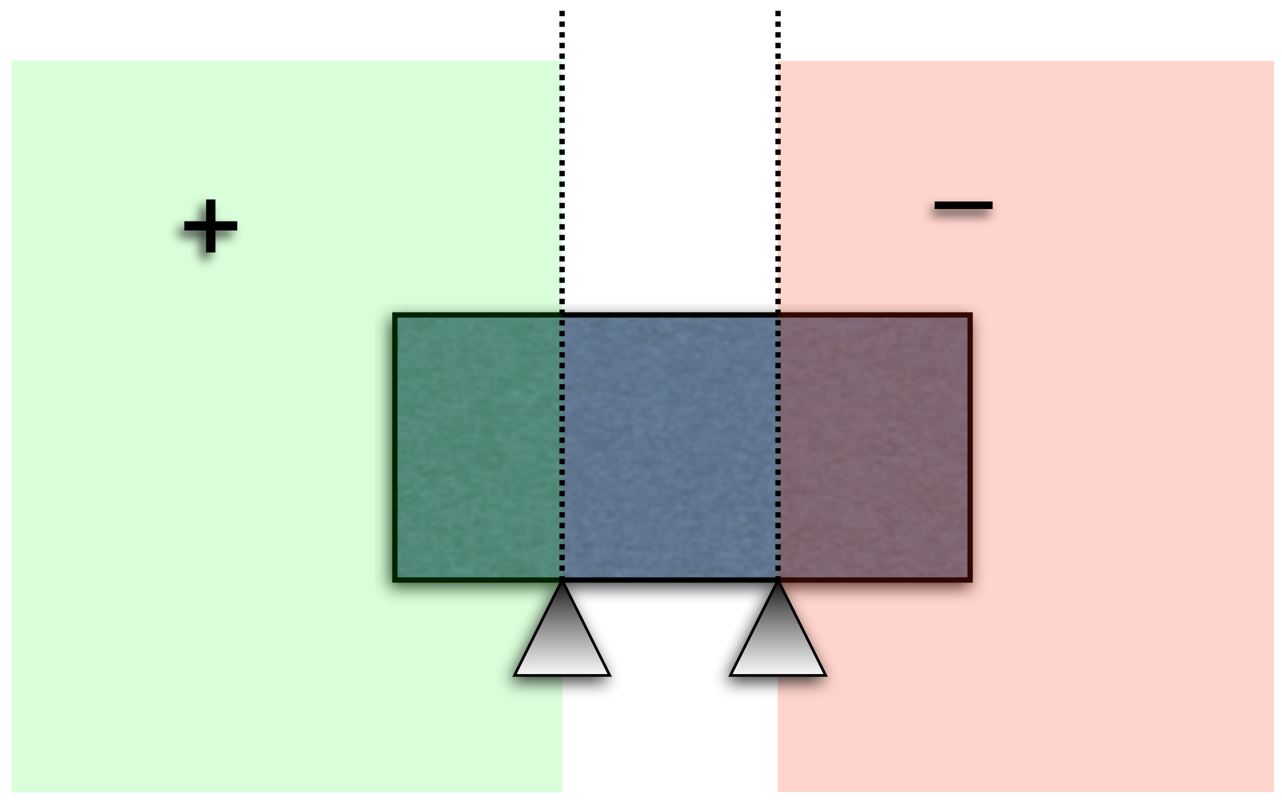
Grasp Analysis: Reuleaux's Method

- Intersect common regions



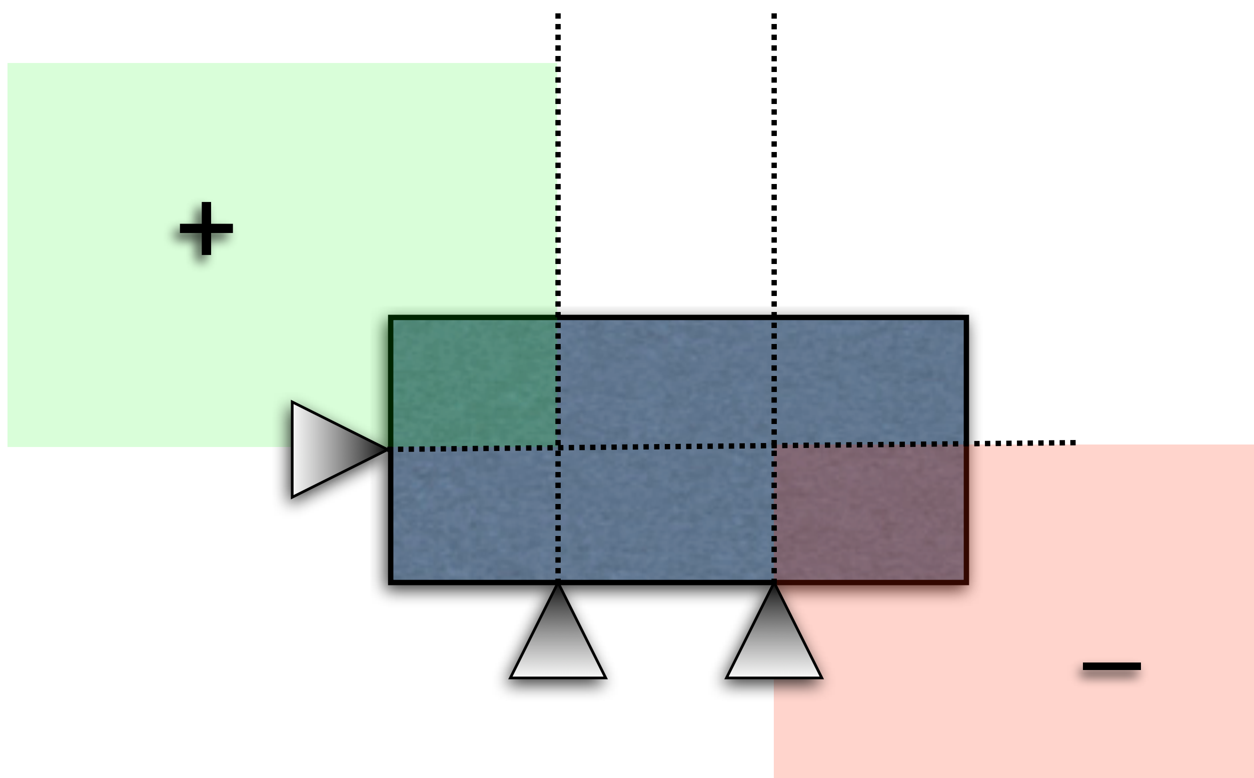
Grasp Analysis: Reuleaux's Method

- Intersect common regions



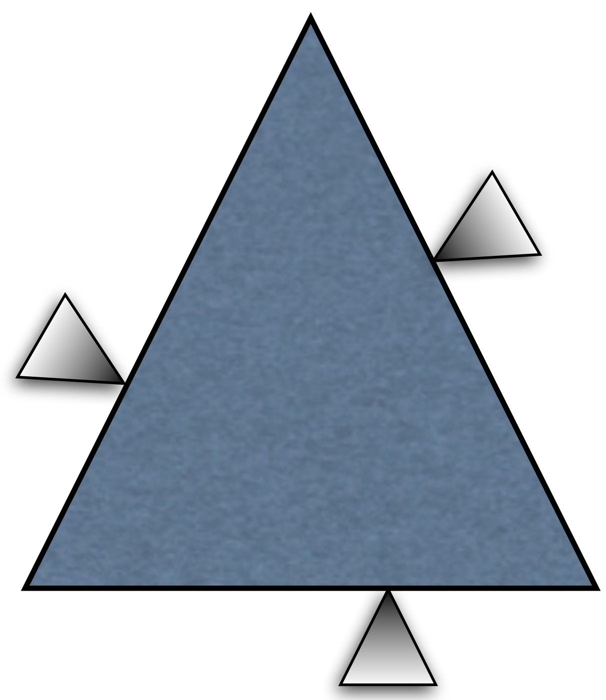
Grasp Analysis: Reuleaux's Method

- Intersect common regions



Grasp Analysis: Reuleaux's Method

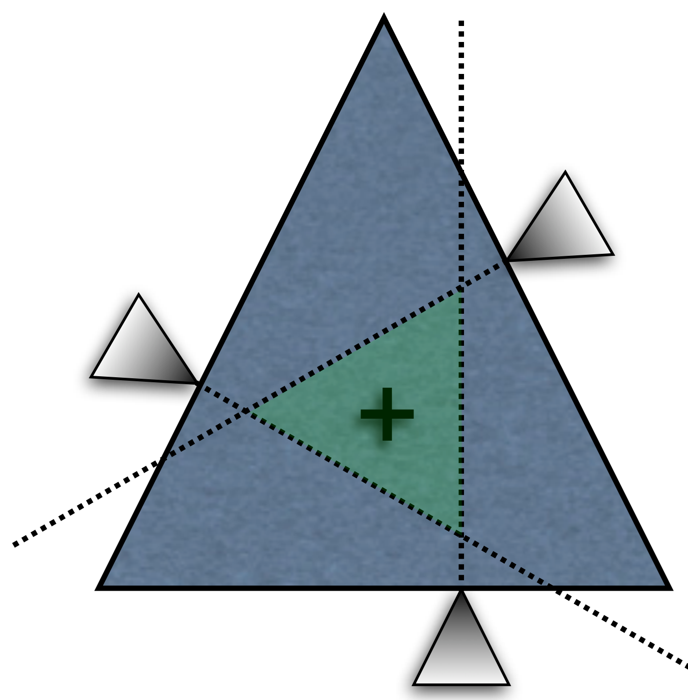
- Another example:



- Is this completely constrained?

Grasp Analysis: Reuleaux's Method

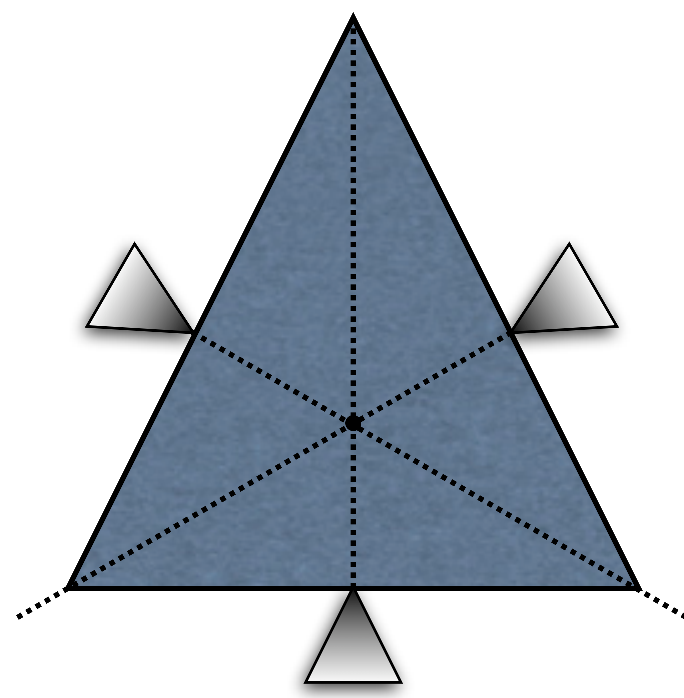
- Another example:



- Can spin counter-clockwise around area in the middle — but not clockwise!

Grasp Analysis: Reuleaux's Method

- How about now?



- Common intersections may indicate, but *do not guarantee*, that rotation is possible

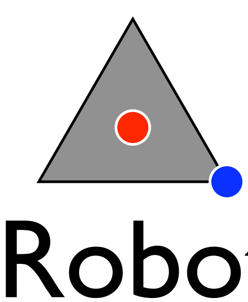
Grasp Analysis: Reuleaux's Method

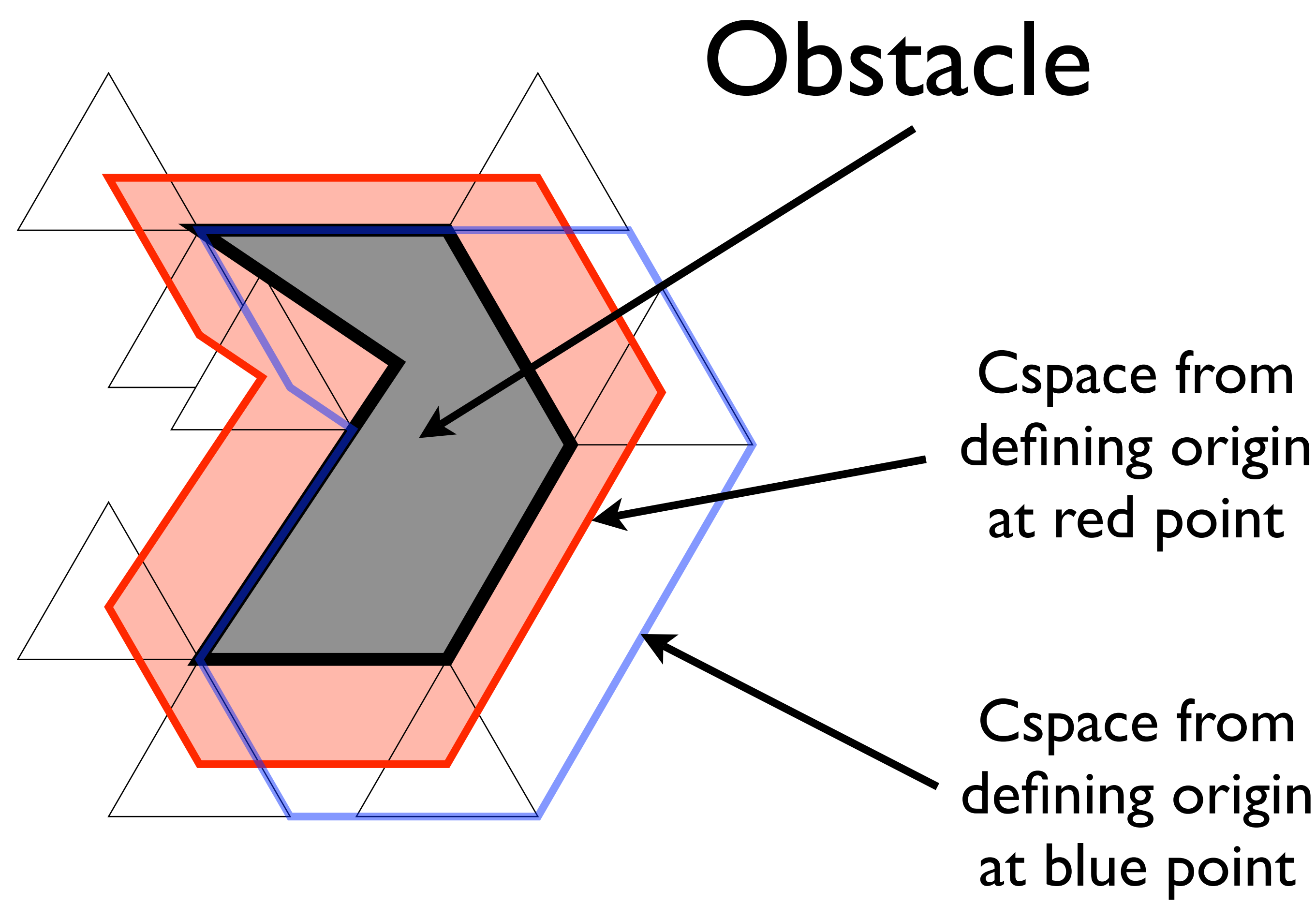
- Reuleaux's Method is good for humans, not so good for machines
- Doesn't extend to three dimensions
- Analytical solution would require a lecture unto itself
  - 16-741: Mechanics of Manipulation
  - Learn about screws, twists, wrenches, and moments

Motion Path Planning

- The Cspace Transform: the set of configuration points around obstacles which would cause a collision

Notice how the Cspace formed by defining the origin of the robot in its center (red dot and outline) is merely a translated version of the Cspace formed by placing the origin at one of the robot's corners (blue dot and outline).





Motion Path Planning

- The Cspace Transform: the area around obstacles which would cause a collision with the robot

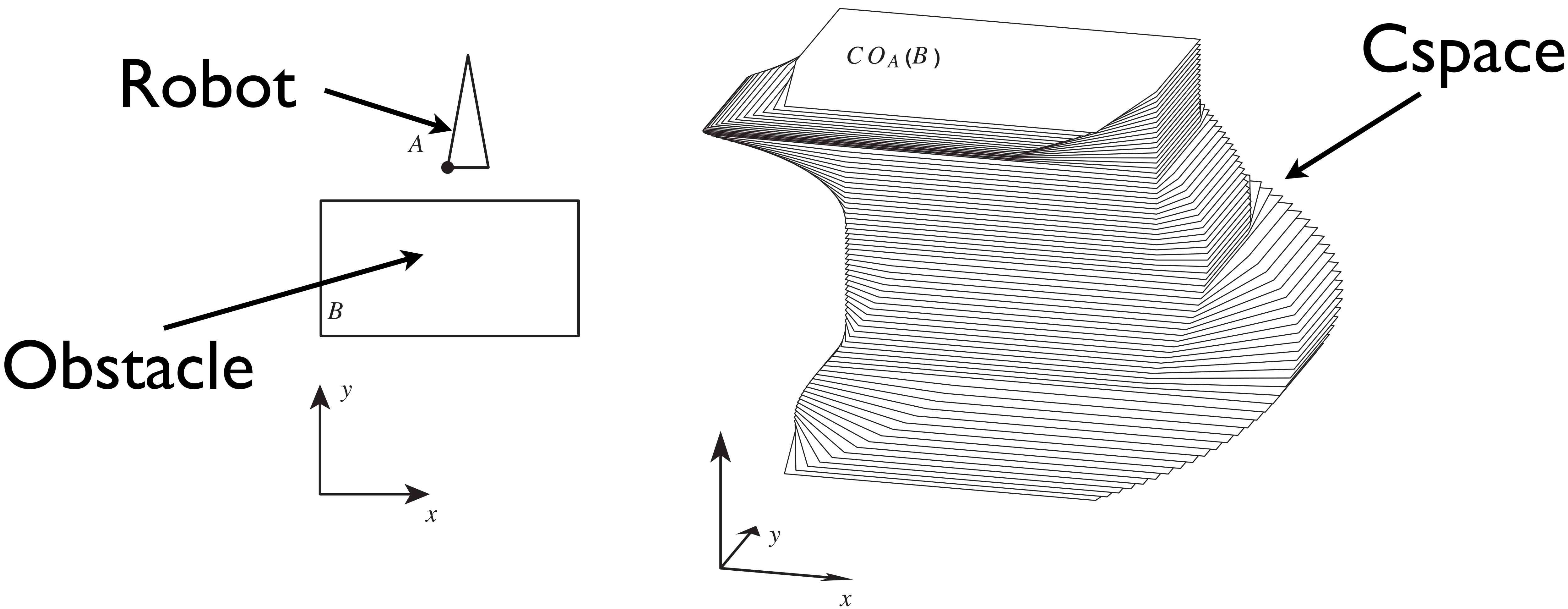
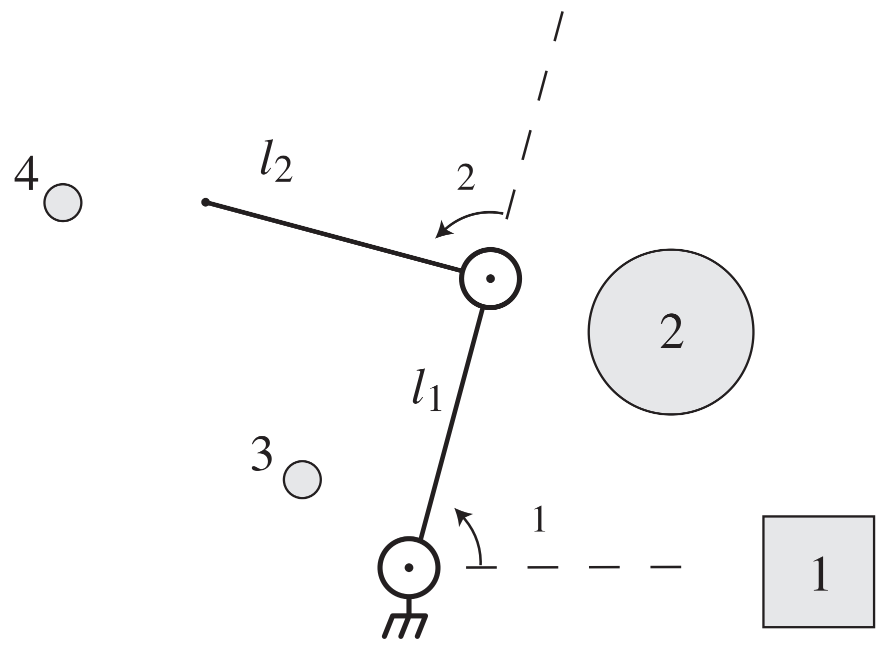


Figure 4.4 - Mason, Mechanics Of Robotic Manipulation

Motion Path Planning

- The Cspace Transform is not just for mobile robots' outer hulls!



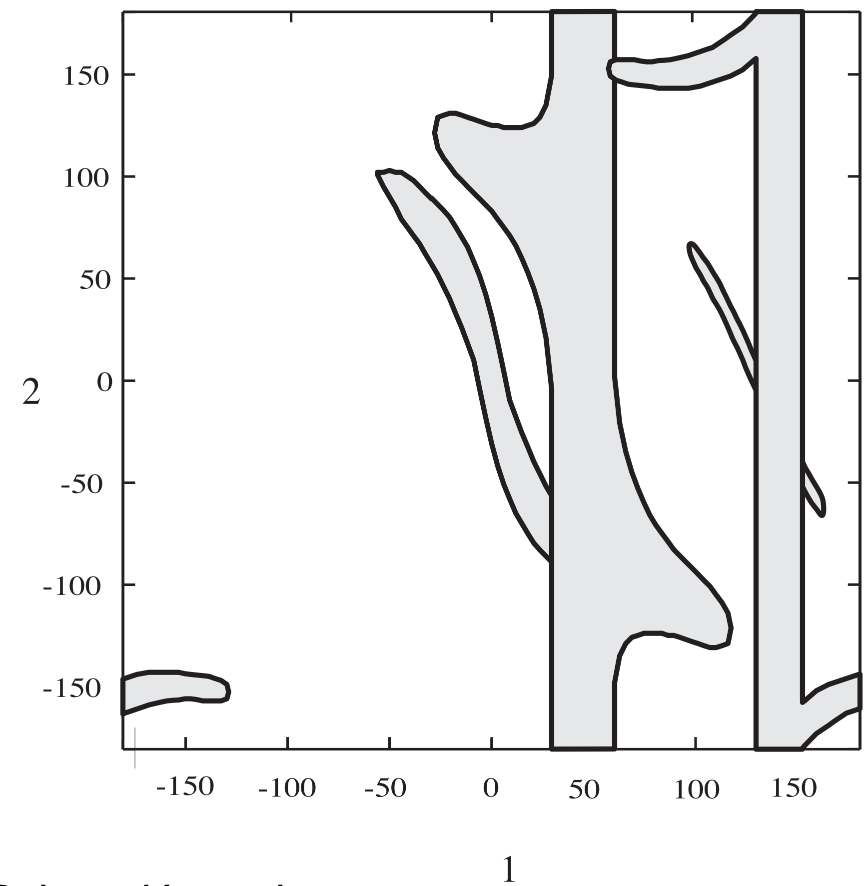


Figure 4.5 - Mason, Mechanics Of Robotic Manipulation

Motion Path Planning

- So, we know where we can't go, but how do we avoid it?
- Approach 1: Visibility Graph
  - Connect visible corners together, search the graph of connected edges

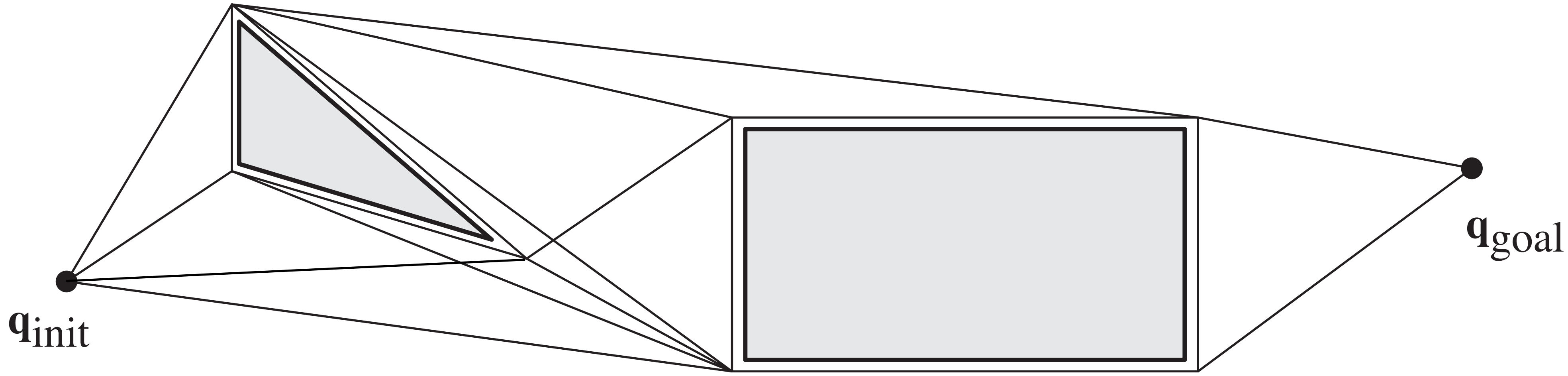
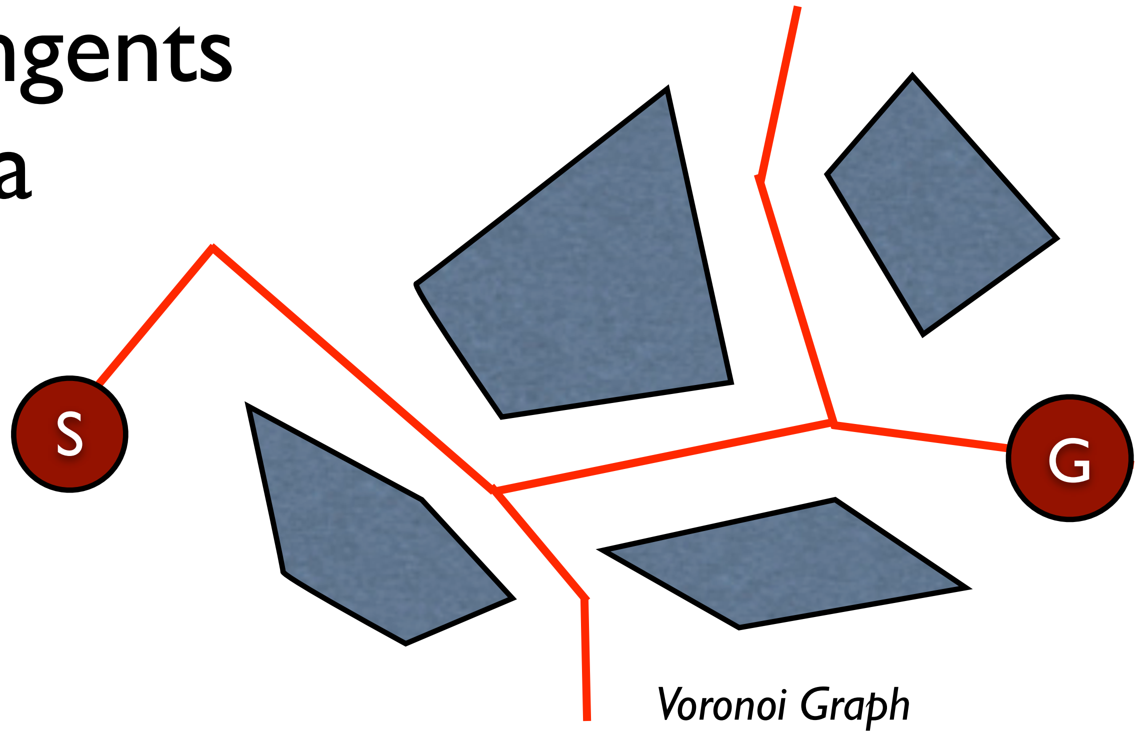


Figure 4.1 - Mason, Mechanics Of Robotic Manipulation

Motion Path Planning: Visibility Graph

- Great for 2 dimensions, but not for more
- Voronoi graphs are similar, and *have* been generalized to higher dimensions (Choset)
  - Instead of a graph of tangents between obstacles, use a graph of the midpoints
  - Fast search, safe path, but suboptimal distance

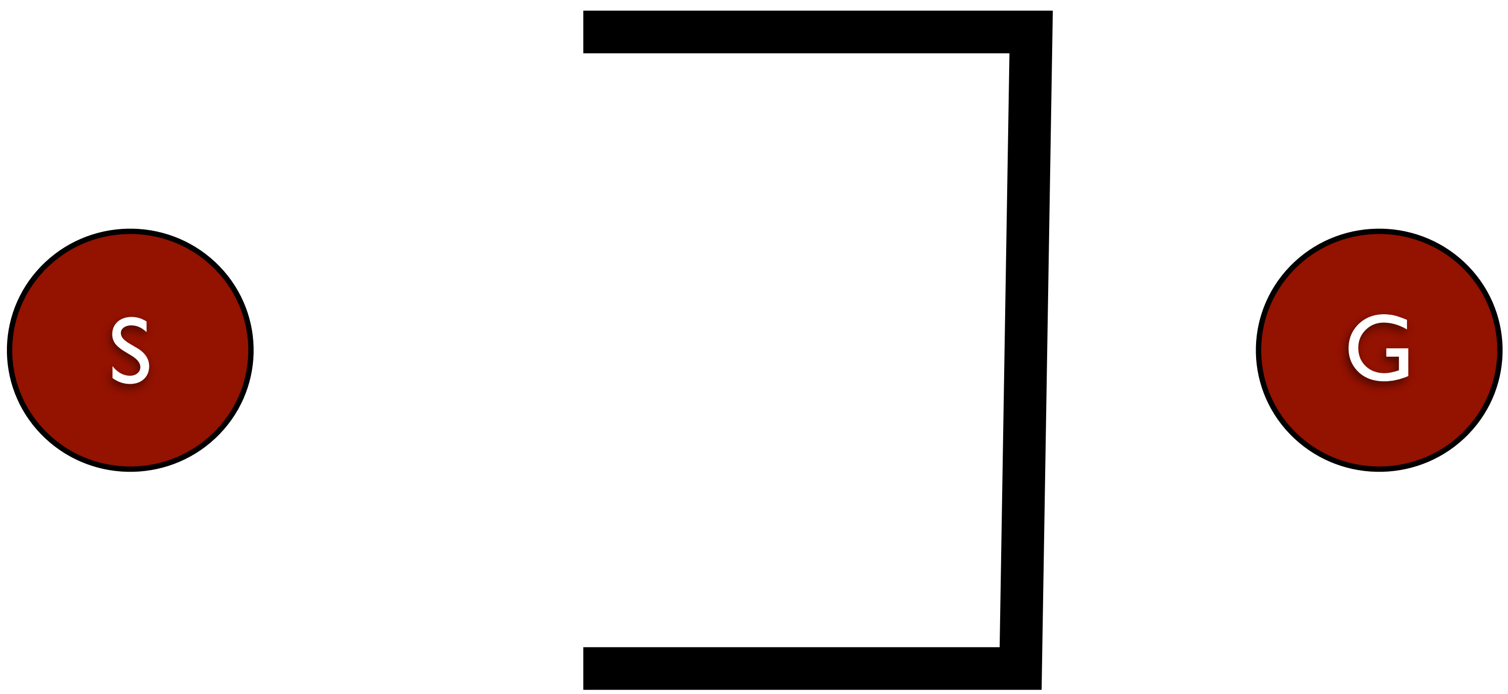


Voronoi Graph

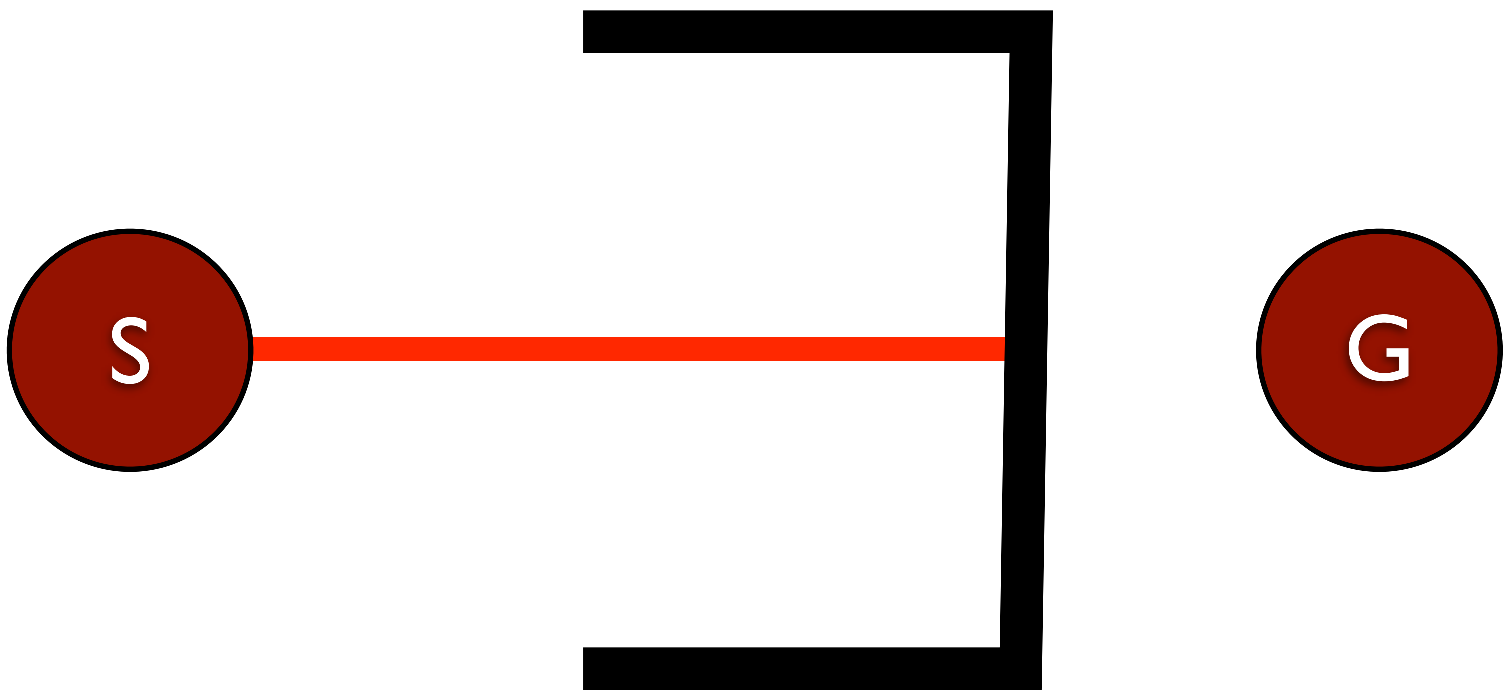
Motion Path Planning: Best First Search (& Friends)

- Don’t explicitly solve all of Cspace before searching
  - Basically, keep a priority queue of unevaluated nodes, sorted by “score” (e.g. distance to goal, or distance to goal plus distance so far)
  - Each iteration, expand the current “best” node
  - Choice of scoring heuristic (if you have a choice!) can make tradeoffs between search speed and optimality of solution found.

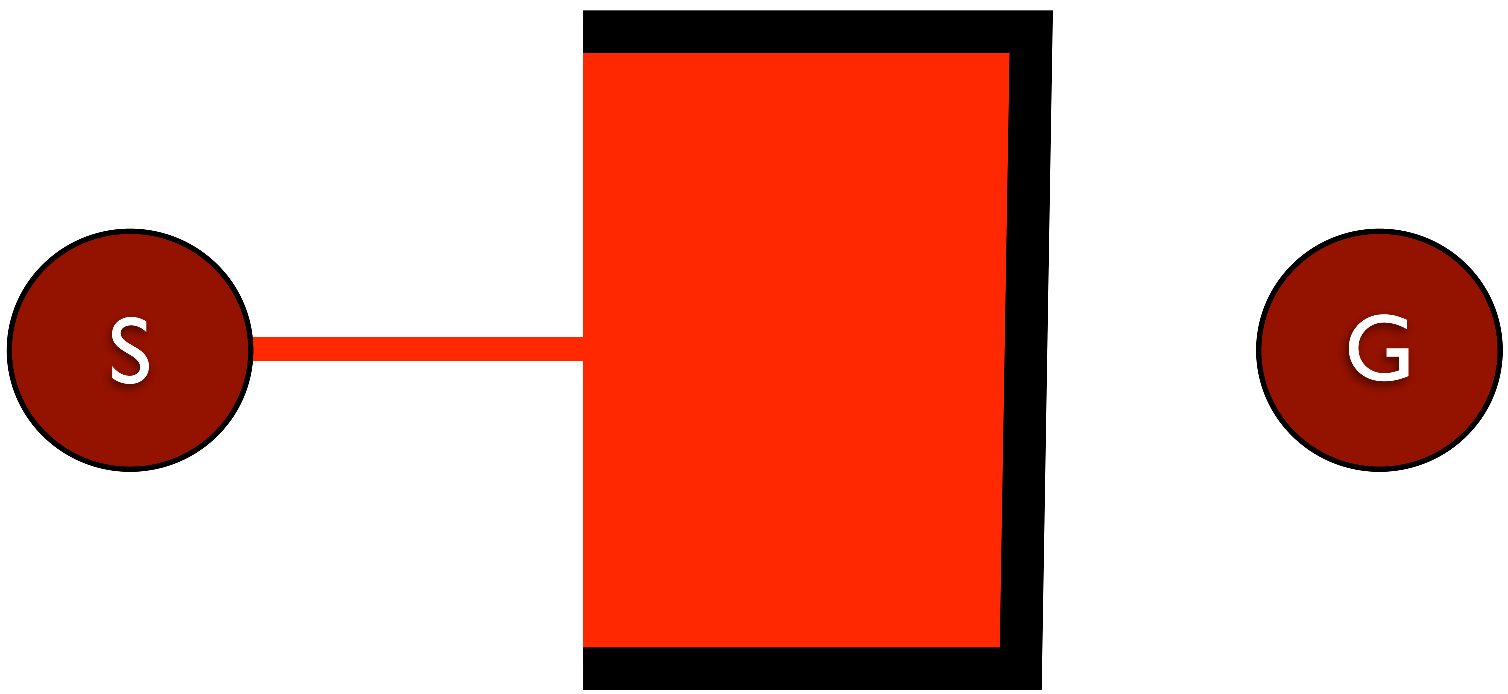
Motion Path Planning: Best First Search (& Friends)



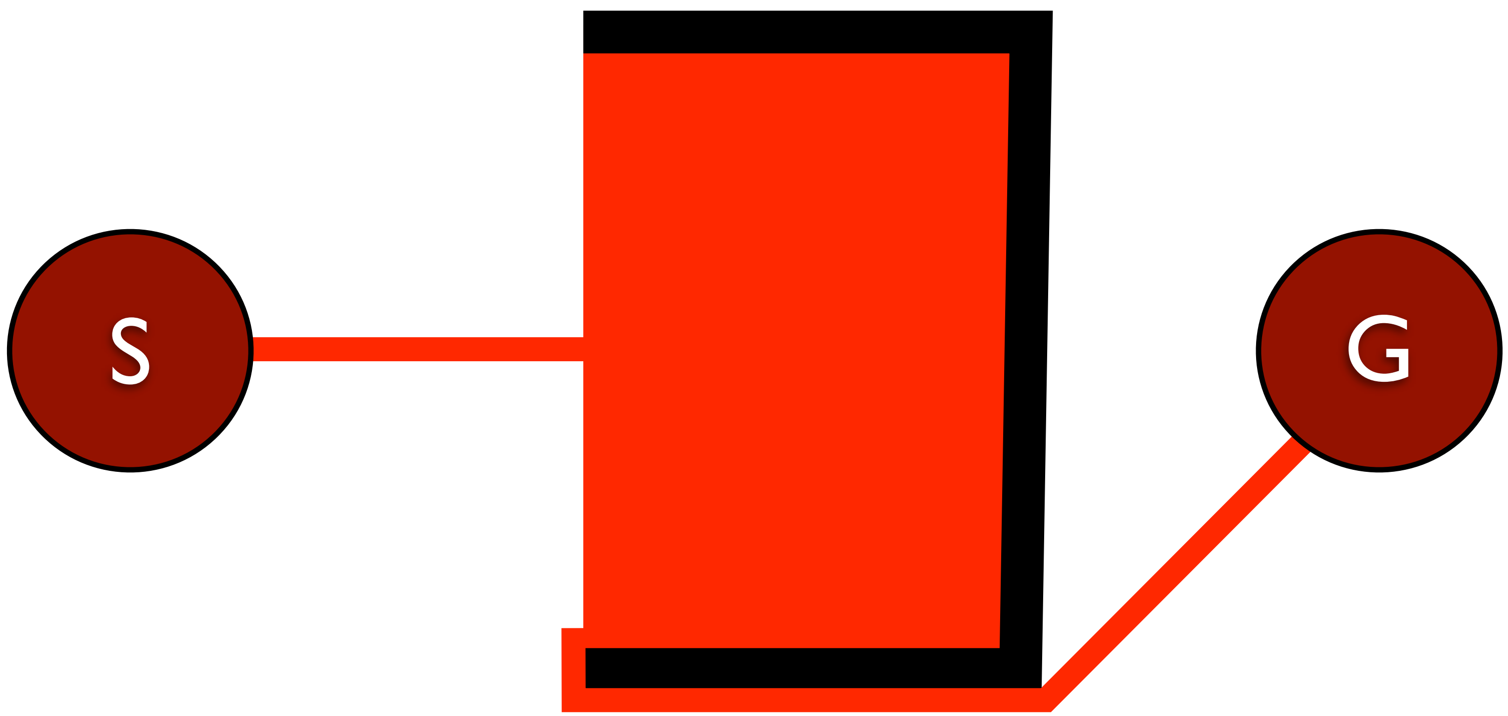
Motion Path Planning: Best First Search (& Friends)



Motion Path Planning: Best First Search (& Friends)



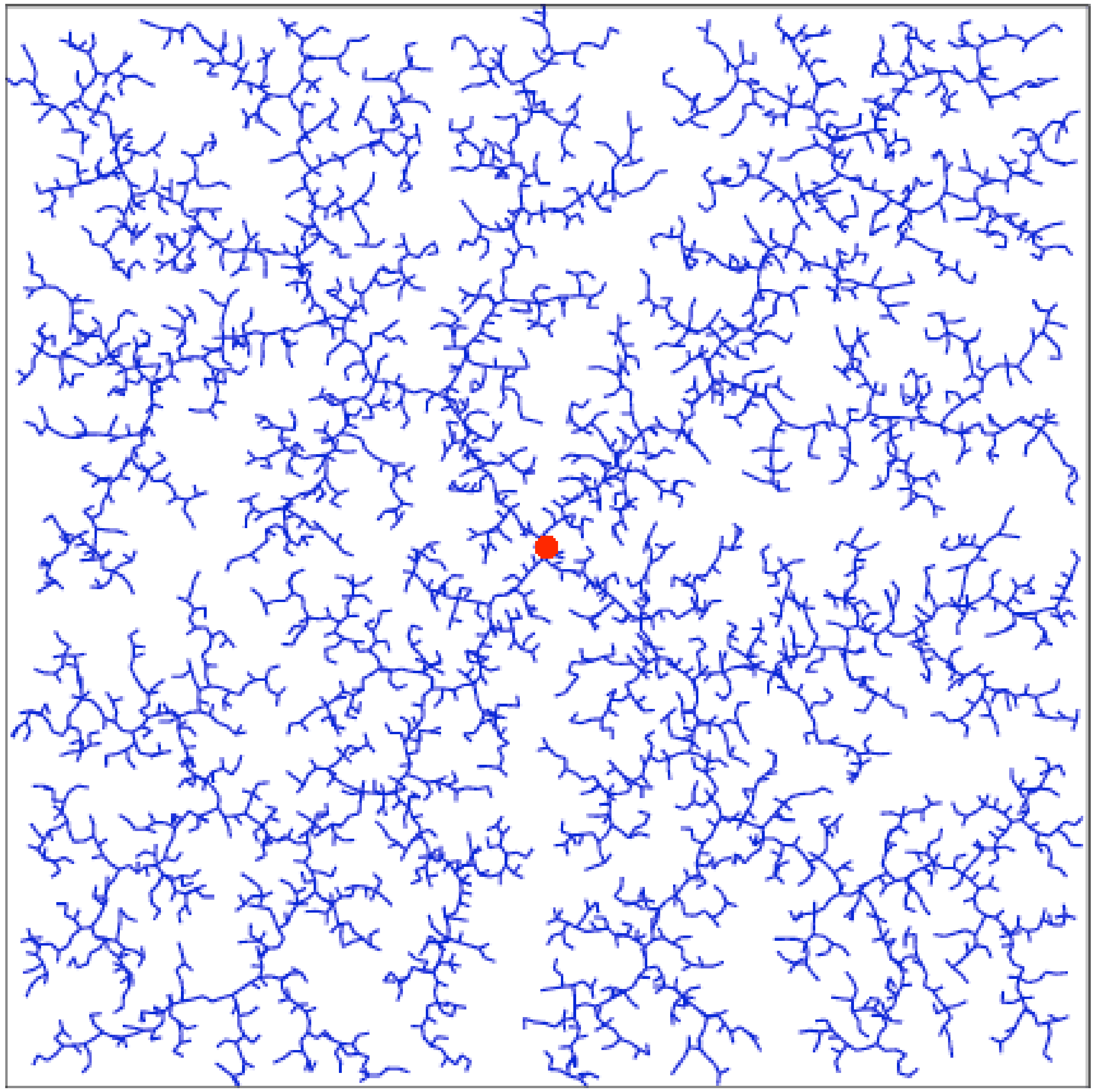
Motion Path Planning: Best First Search (& Friends)



Motion Path Planning: Rapidly Exploring Random Trees

- LaValle 1998
- Repeat *K* times:
  - Pick a random configuration point *P*
  - Find *N*, the closest tree node to *P*
  - Add new node *N*', some distance Δ from *N* toward *P*
- Back to exploring entire configuration space?
- Not necessarily — bias the random target to pick the goal more often

Motion Path Planning: Rapidly Exploring Random Trees



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

Motion Path Planning: Potential Fields

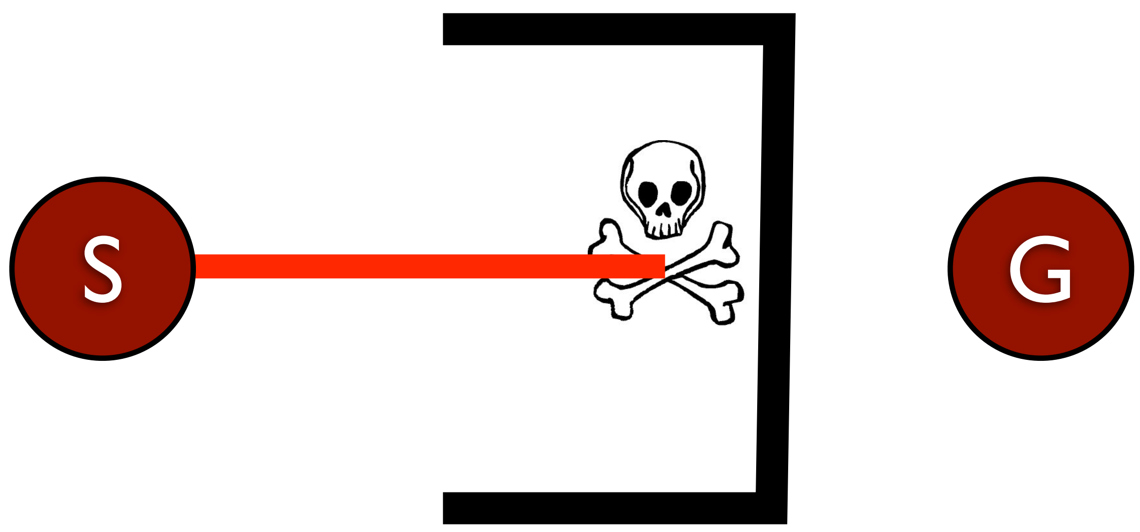
- So far we've been assuming we already know the environment, and there aren't other agents changing things around!
- Constant replanning is costly
  - replan only when something is amiss
  - replan only affected parts of existing plan (open research problem!)
- Or… don't make a plan in the first place

Motion Path Planning: Potential Fields

- Define a function *f* mapping from a specified configuration to a score value
  - e.g. distance to goal plus distance to obstacles
- Essentially just running heuristic from before:
  - Evaluate each of the currently available moves
  - Pick the one which maximizes score (or in example above, minimizes cost)

Motion Path Planning: Potential Fields

- Downside: can get stuck in local minima



- Workaround: follow edges ("bug" method)
- Upside: extremely quick and reactive
  - Popular in robosoccer for navigating to ball

Motion Path Planning: Summary

- Known Environment, Deterministic Actions
  - Road Maps (Visibility, Voronoi), A*, RRT, brushfire
- Unknown Environment, Deterministic Actions
  - Potential Field, "Bug", D*
- Non-Deterministic and/or Unknown Environment
  - MDP, POMDP

Getting Back to the AIBO

- Under-actuated manipulators
  - use the ground and other objects to help
- Don't get hung up on grasp closure
  - we're not handling nuclear waste — equilibrium is enough for our purposes!

Getting Back to the AIBO: Where we want to go

- Develop larger library of motion primitives
  - How to push a banana? One leg? Two legs? Head nuzzle?
  - Each strategy has advantages, but have to quantify these capabilities so planners can choose among them
- Learn models of the environment from experience

Next Time:

Dynamics!
Friction, Forces, and Control

Thanks to:
16-741: Mechanics of Manipulation (Mason)
16-830: Planning, Execution, and Learning (Rizzi, Veloso)