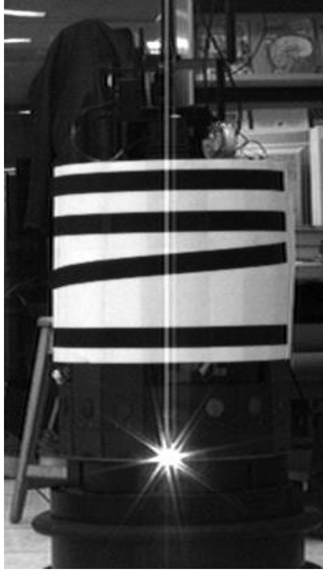
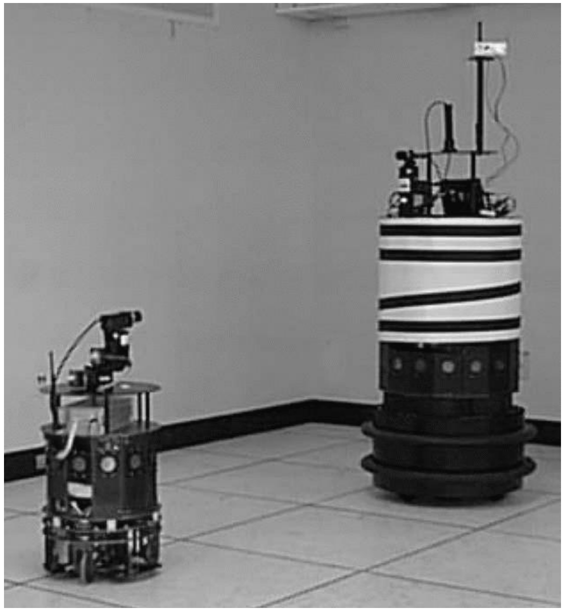
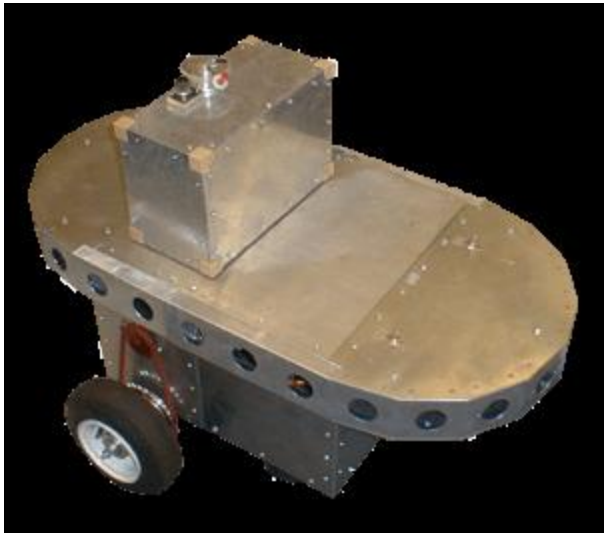
Outline

- The robots I worked with
- Path Planning
  - Visibility Graph
  - Bug Algorithms
  - Potential Fields
  - Skeletons/Voronoi Graphs
  - C-Space

McGill University

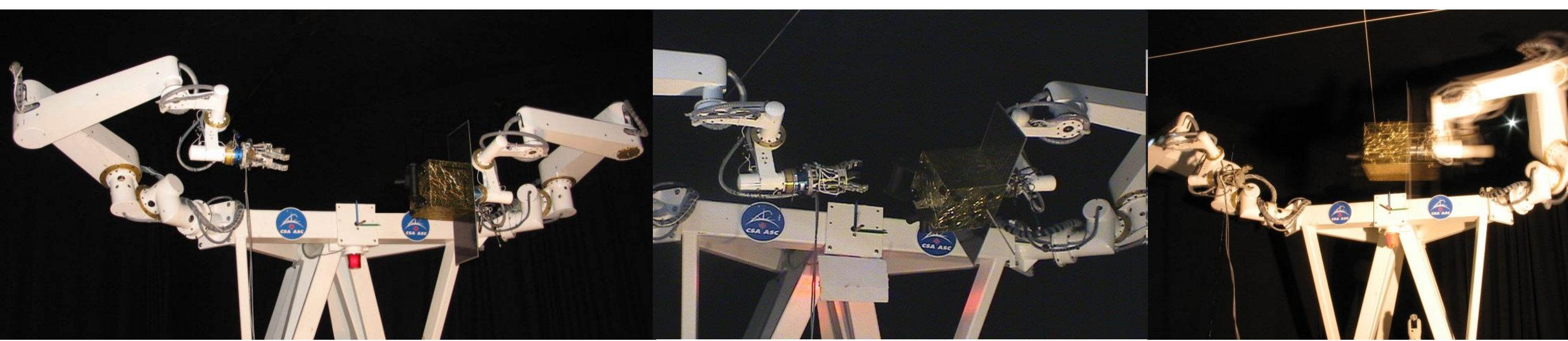






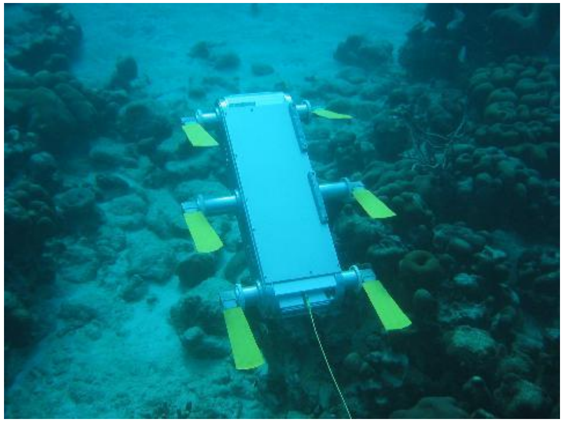

iRobot
Roomba

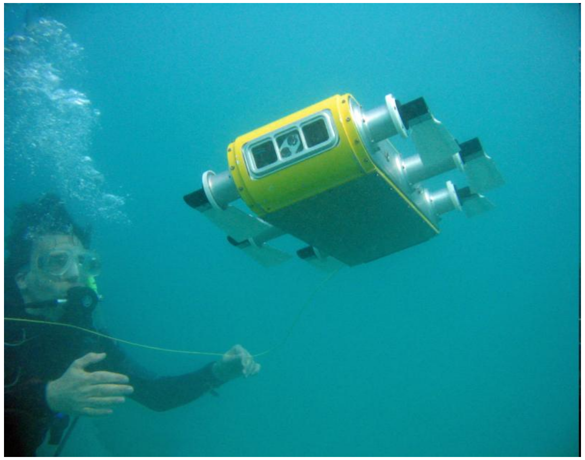
Canadian Space Agency

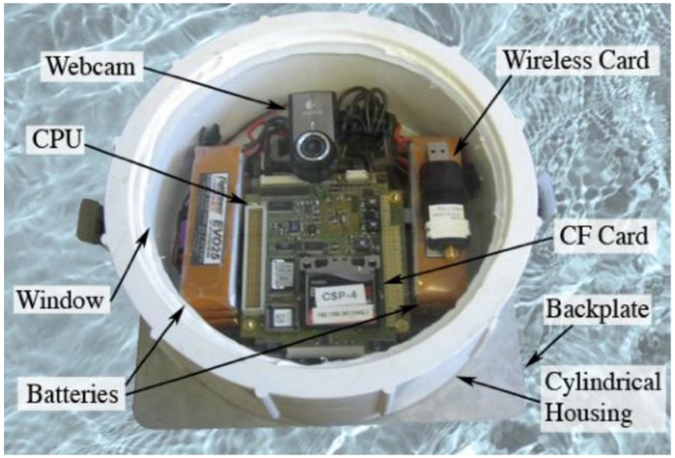


McGill University

McGill Centre for Intelligent Machines



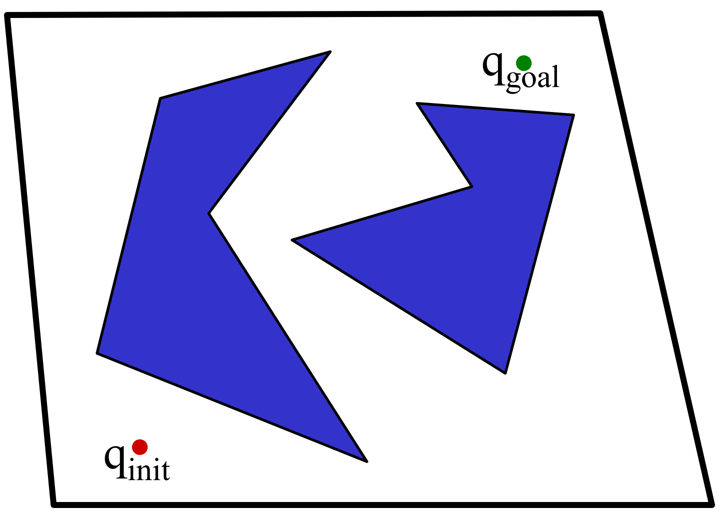


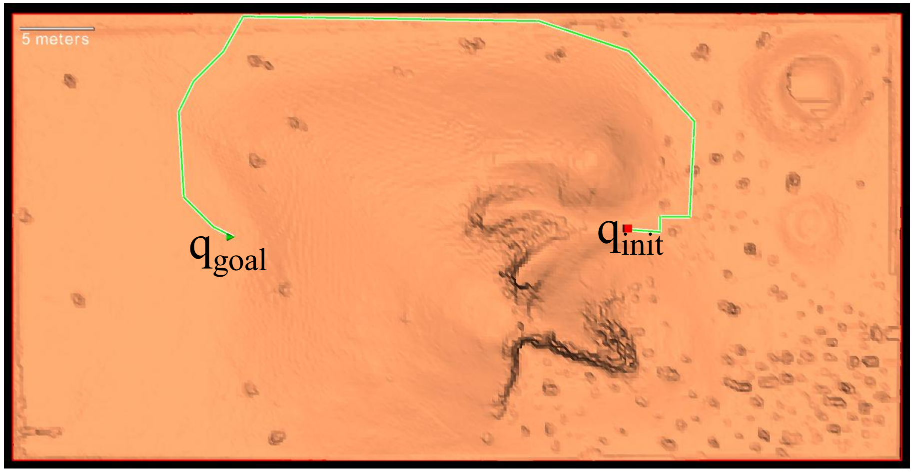


Motion Planning

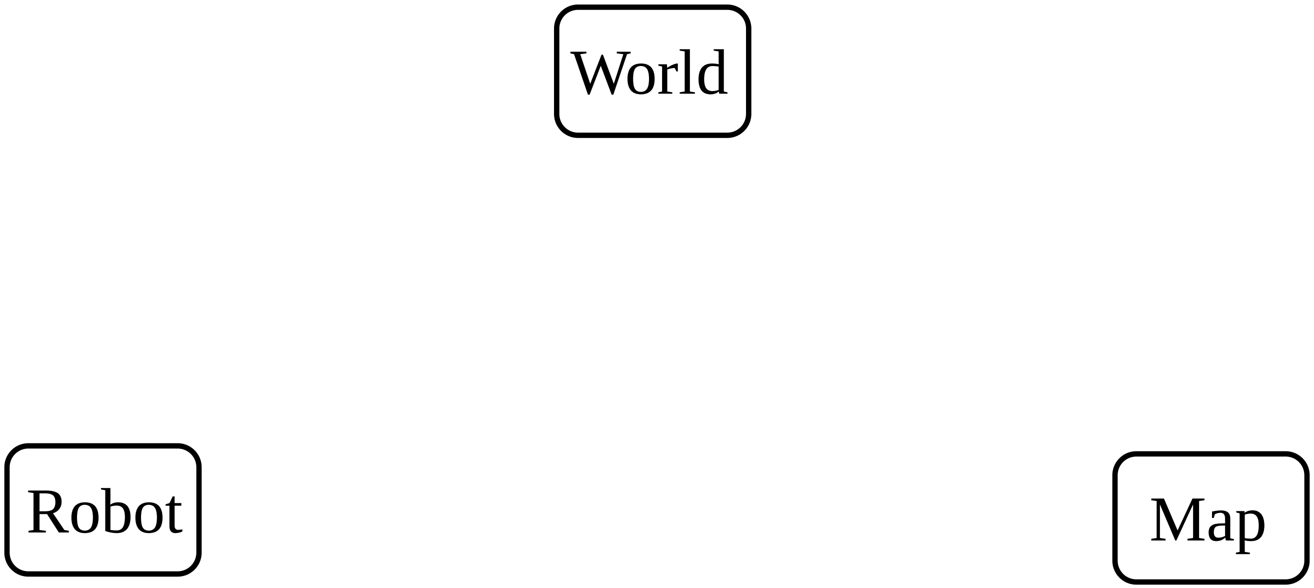
- The ability to go from **A** to **B**
  - Known map – Off-line planning
  - Unknown Environment –Online planning
  - Static/Dynamic Environment

• q_{init} • q_{goal}





Path Planning



Path Planning

World

- Indoor/Outdoor
- 2D/2.5D/3D
- Static/Dynamic
- Known/Unknown
- Abstract (web)

Robot

Map

Path Planning

World

Robot

Map

- Mobile
  - Indoor/Outdoor
  - Walking/Flying/Swimming
- Manipulator
- Humanoid
- Abstract

Path Planning

World

Robot

Map

- Topological
- Metric
- Feature Based
- 1D,2D,2.5D,3D

Path Planning

World

- Indoor/Outdoor
- 2D/2.5D/3D
- Static/Dynamic
- Known/Unknown
- Abstract (web)

Robot

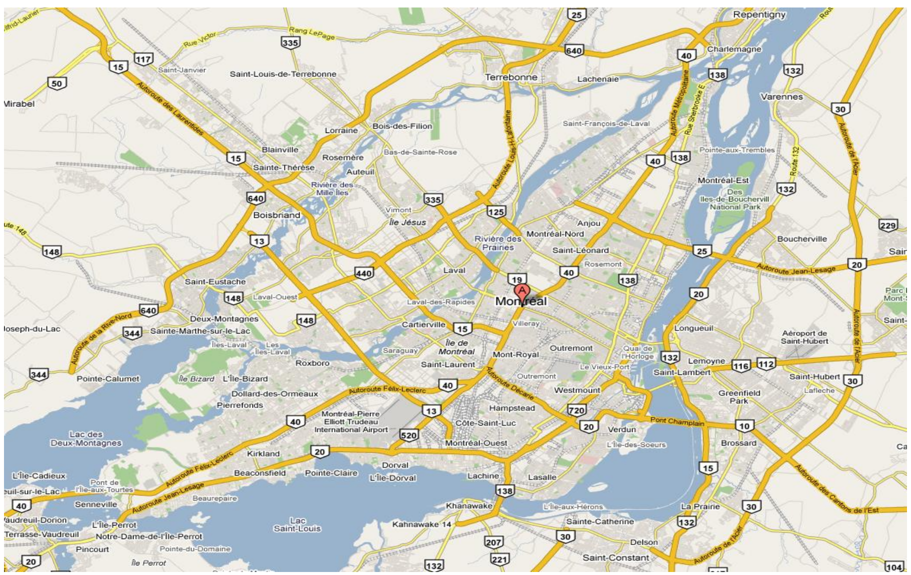
- Mobile
  - ➢Indoor/Outdoor
  - ➢Walking/Flying/Swimming
- Manipulator
- Humanoid
- Abstract

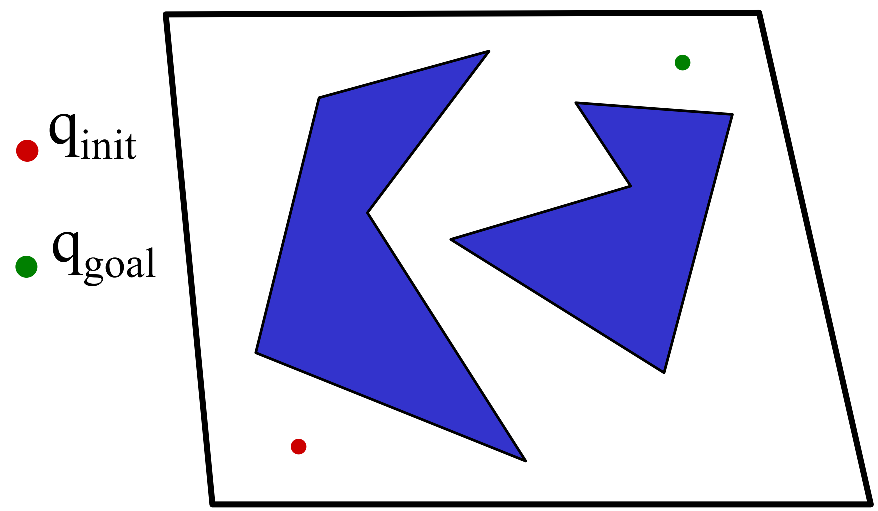
Map

- Topological
- Metric
- Feature Based
- 1D,2D,2.5D,3D

Path Planning: Assumptions

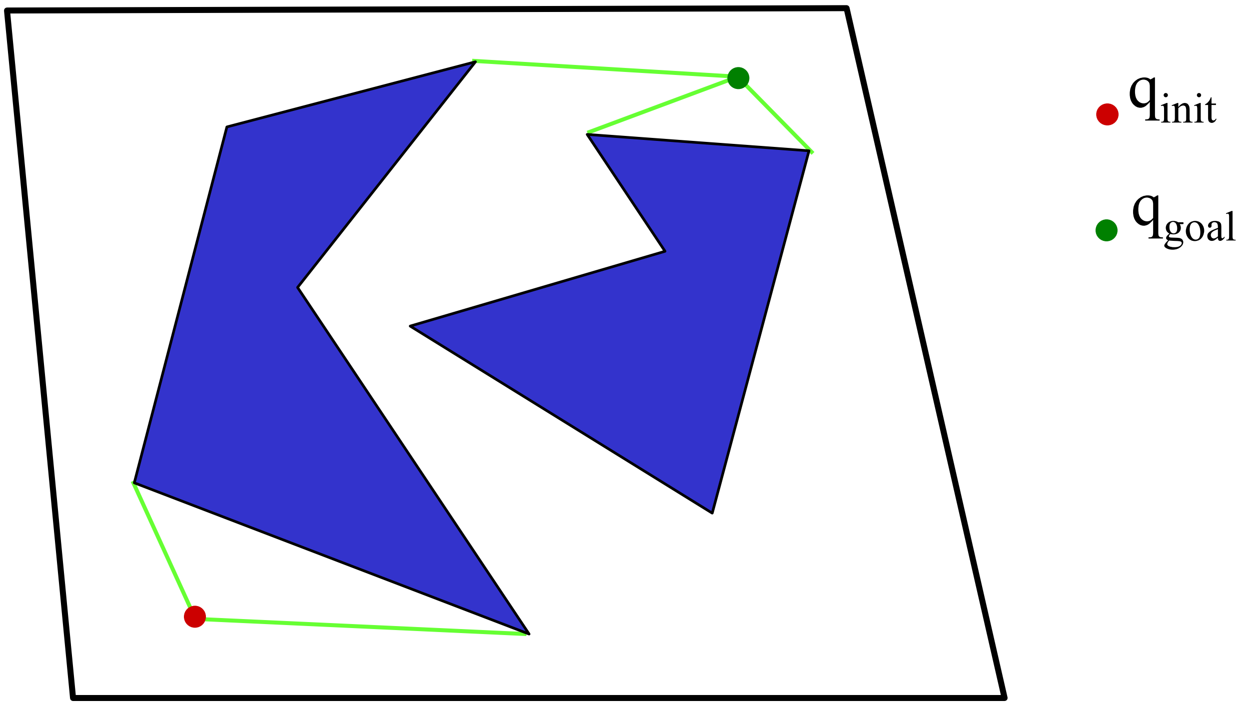
- Known Map
- Roadmaps (Graph representations)
- Polygonal Representation





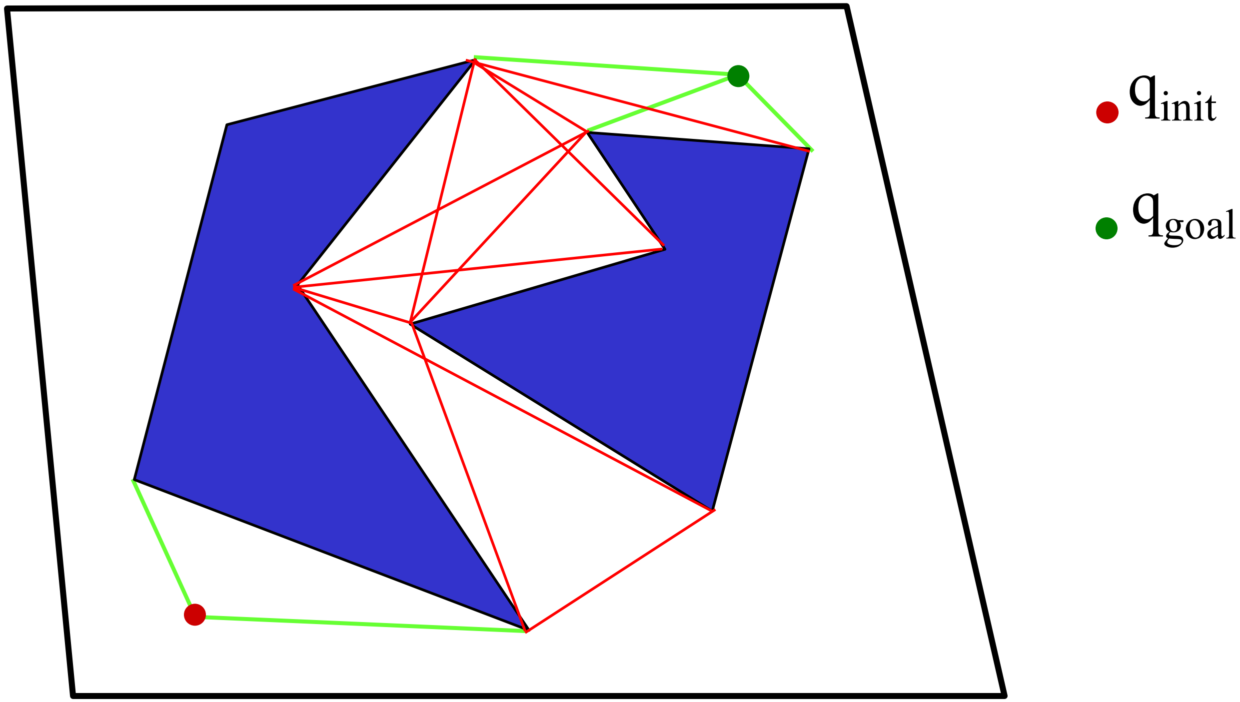
Visibility Graph

- Connect Initial and goal locations with all the visible vertices



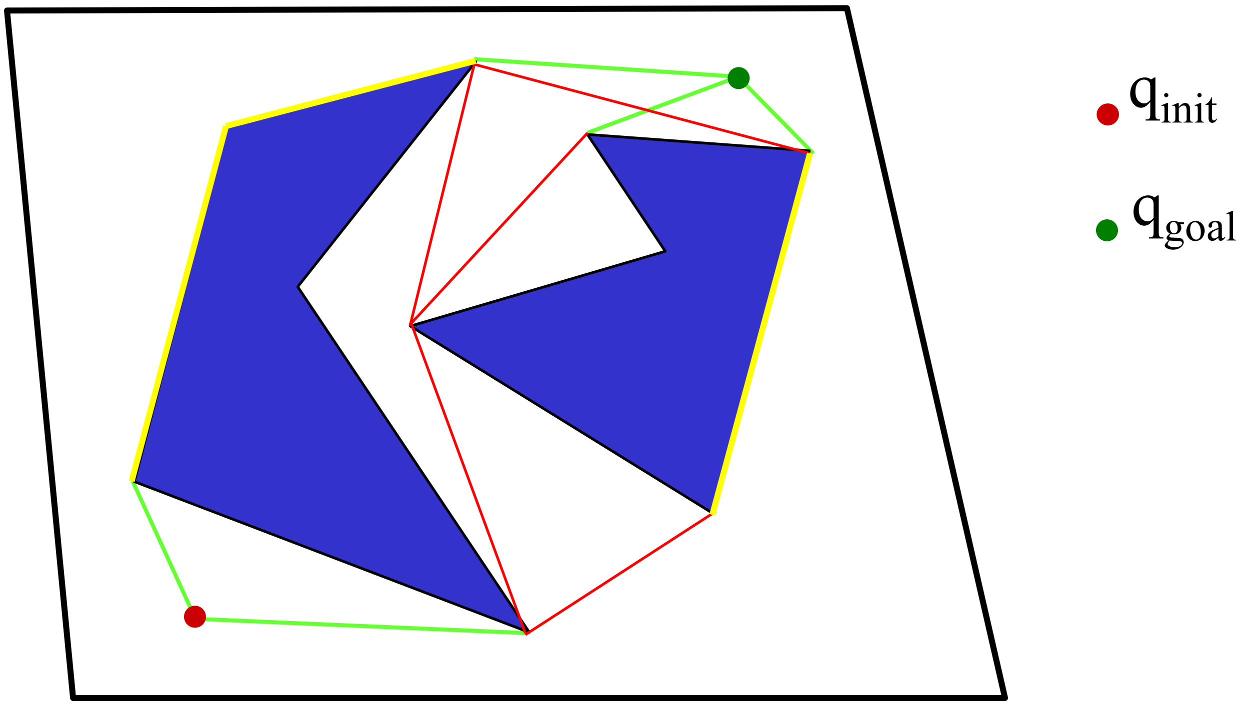
Visibility Graph

- Connect initial and goal locations with all the visible vertices
- Connect each obstacle vertex to every visible obstacle vertex



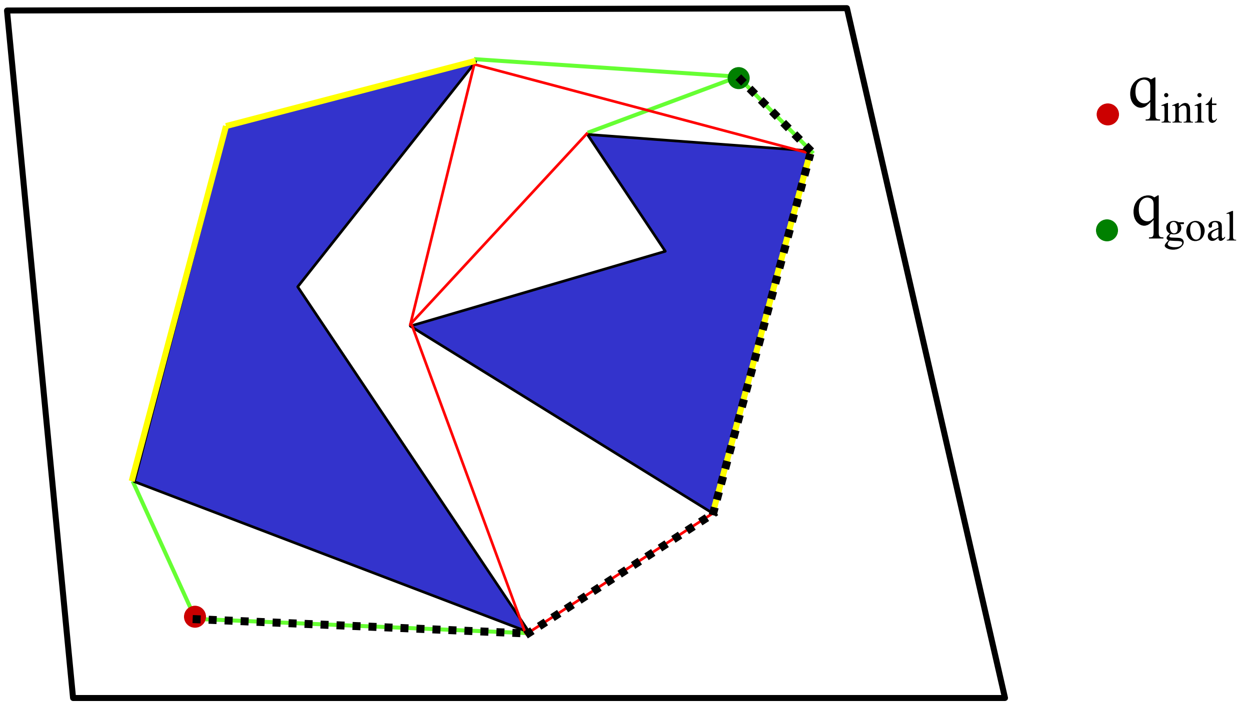
Visibility Graph

- Connect initial and goal locations with all the visible vertices
- Connect each obstacle vertex to every visible obstacle vertex
- Remove edges that intersect the interior of an obstacle



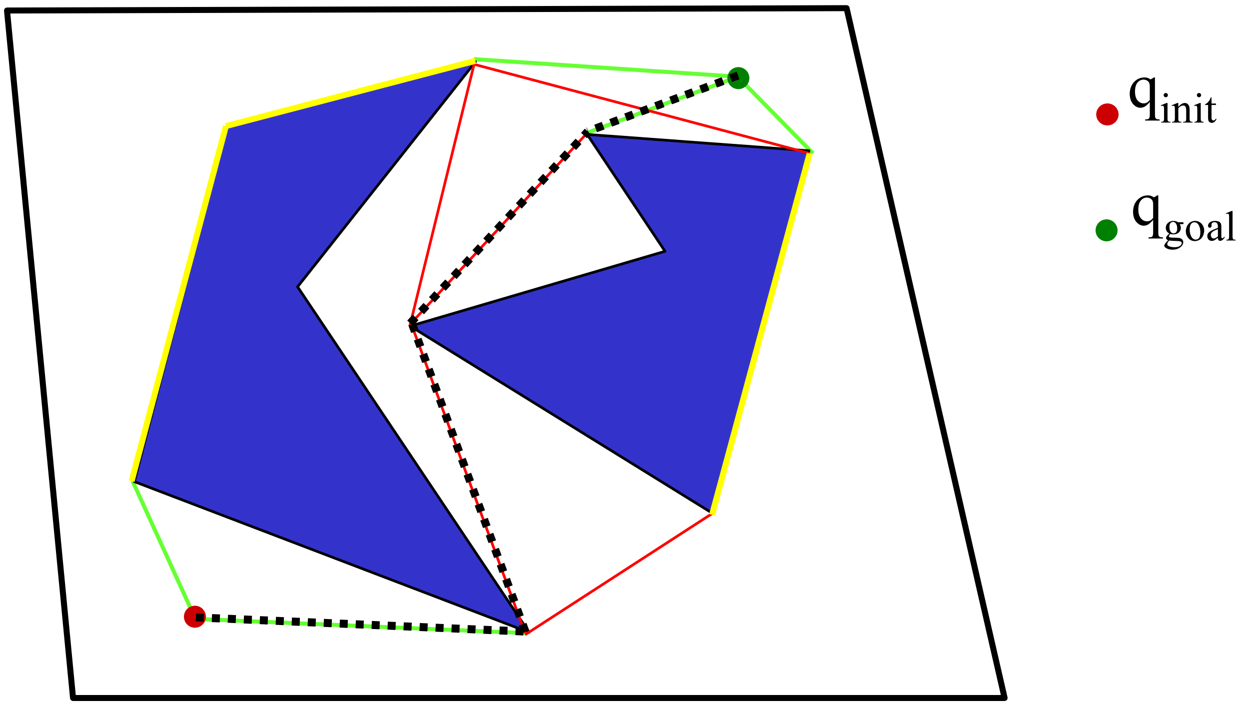
Visibility Graph

- Connect initial and goal locations with all the visible vertices
- Connect each obstacle vertex to every visible obstacle vertex
- Remove edges that intersect the interior of an obstacle
- Plan on the resulting graph



Visibility Graph

- An alternative path
- Alternative name: “Rubber band algorithm”

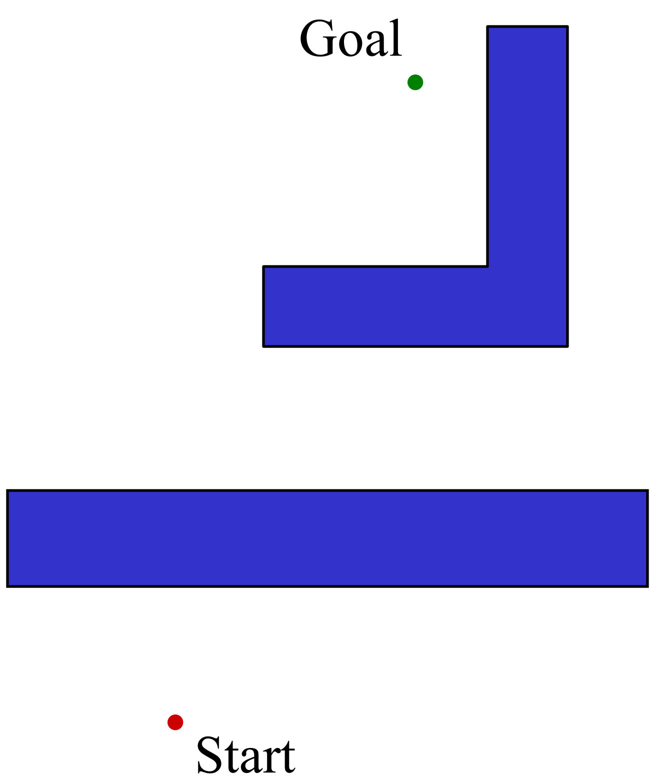


Major Fault

- Point robot
- Path planning like that guarantees to hit the obstacles

Limited-knowledge path planning

Path planning with limited knowledge
- Insect-inspired “bug” algorithms



- known direction to goal
- otherwise local sensing

  walls/obstacles encoders

- “reasonable” world

  1) finitely many obstacles in any finite disc

  2) a line will intersect an obstacle finitely many times

Not truly modeling bugs...

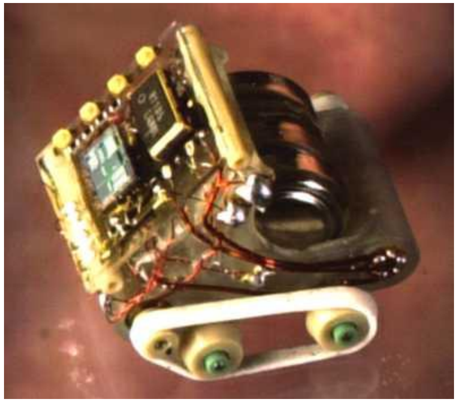
Insects do use several cues for navigation:

visual landmarks

polarized light

chemical sensing

they're not ears...



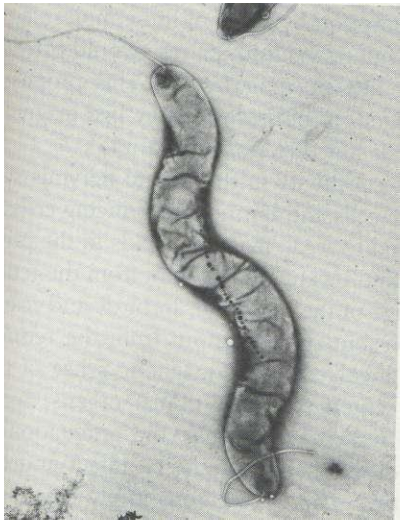
neither are the current bug-sized robots

Other animals use information from

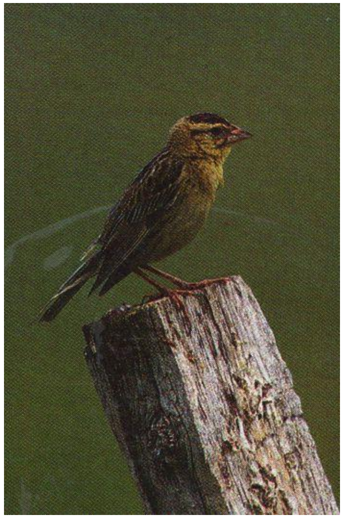
magnetic fields

electric currents

temperature



bacteria



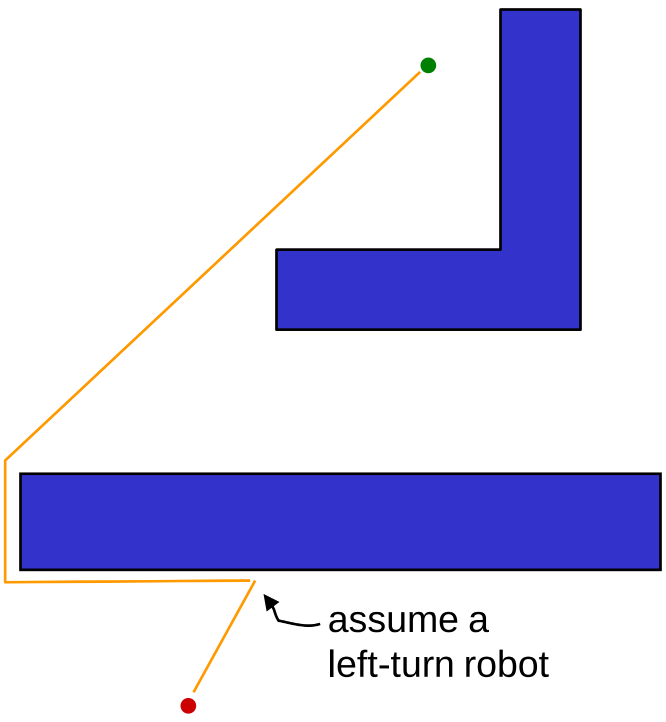
migrating bobolink

Bug Strategy

Insect-inspired "bug" algorithms

- known direction to goal
- otherwise only local sensing

walls/obstacles encoders



"Bug 0" algorithm

1) head toward goal

2) follow obstacles until you can head toward the goal again

3) continue

Does It Work?

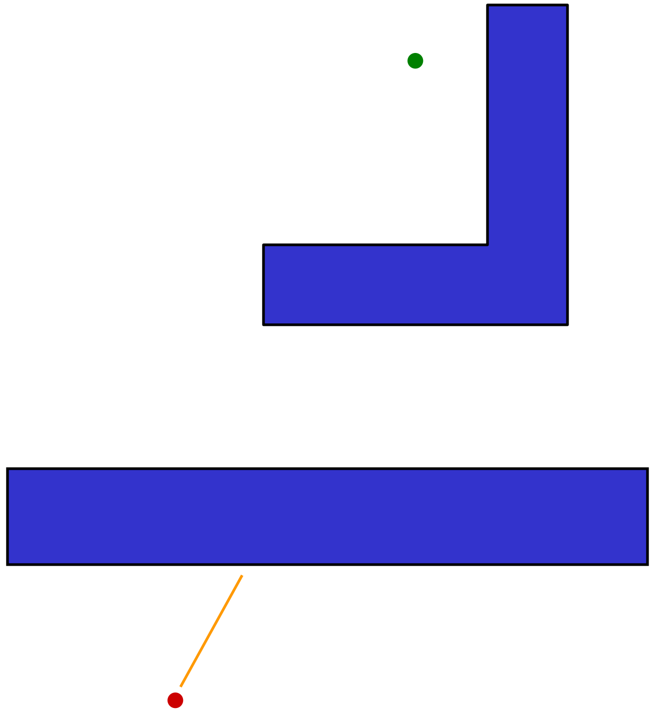
Bug 1

Insect-inspired “bug” algorithms

• known direction to goal

• otherwise only local sensing

walls/obstacles   encoders



“Bug 1” algorithm

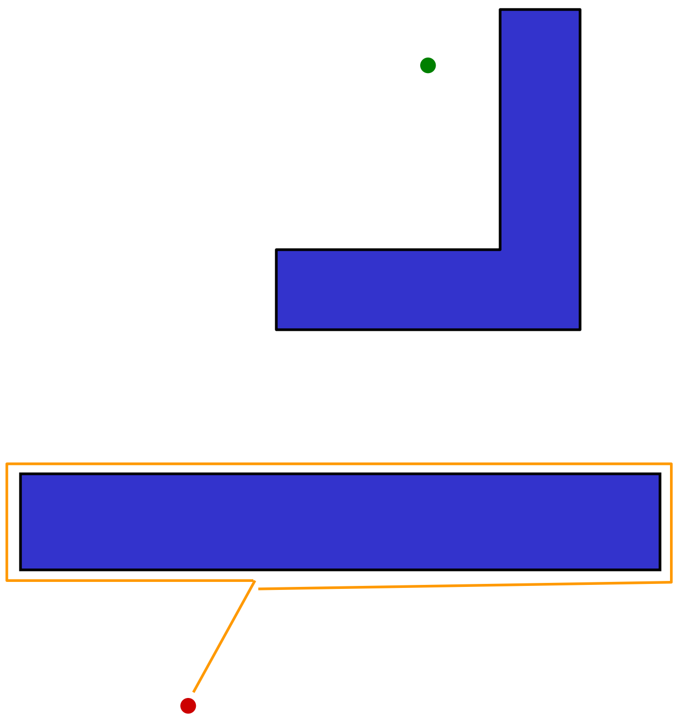
1) head toward goal

Bug 1

Insect-inspired “bug” algorithms

- known direction to goal
- otherwise only local sensing

walls/obstacles   encoders



“Bug 1” algorithm

1) head toward goal

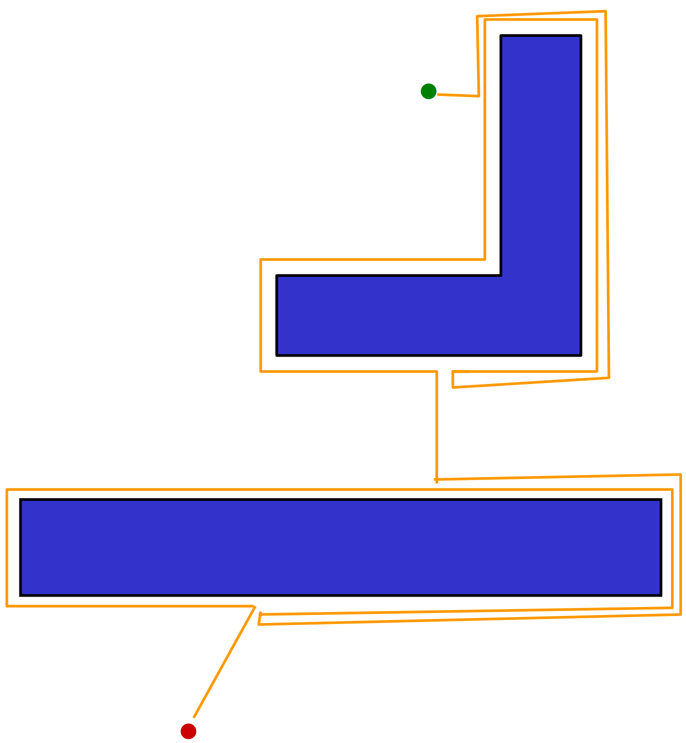
2) if an obstacle is encountered, circumnavigate it *and* remember how close you get to the goal

Bug 1

Insect-inspired “bug” algorithms

- known direction to goal
- otherwise only local sensing

walls/obstacles encoders



“Bug 1” algorithm

1) head toward goal

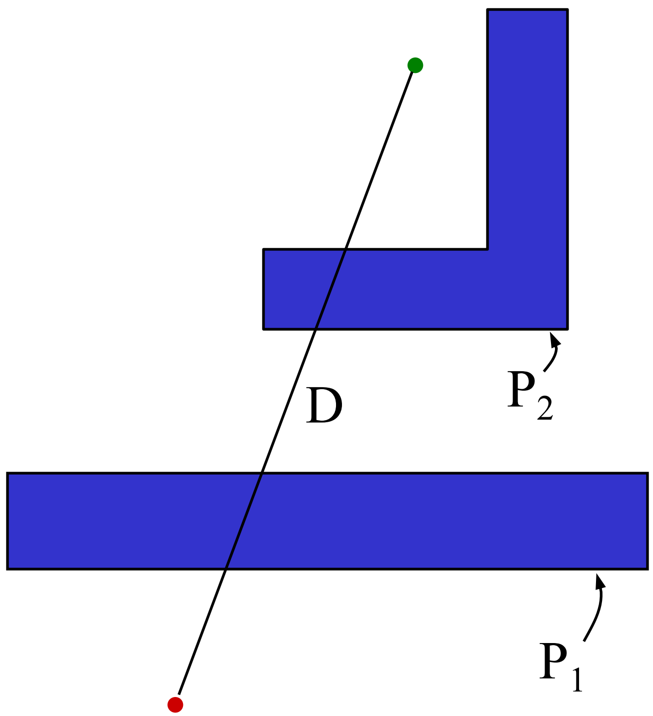
2) if an obstacle is encountered, circumnavigate it *and* remember how close you get to the goal

3) return to that closest point (by wall-following) and continue

Vladimir Lumelsky & Alexander Stepanov Algorithmica 1987

Bug 1 analysis

Distance Traveled



What are bounds on the path length that the robot takes?

Available Information:

D = straight-line distance from start to goal

P_i = perimeter of the *i* th obstacle

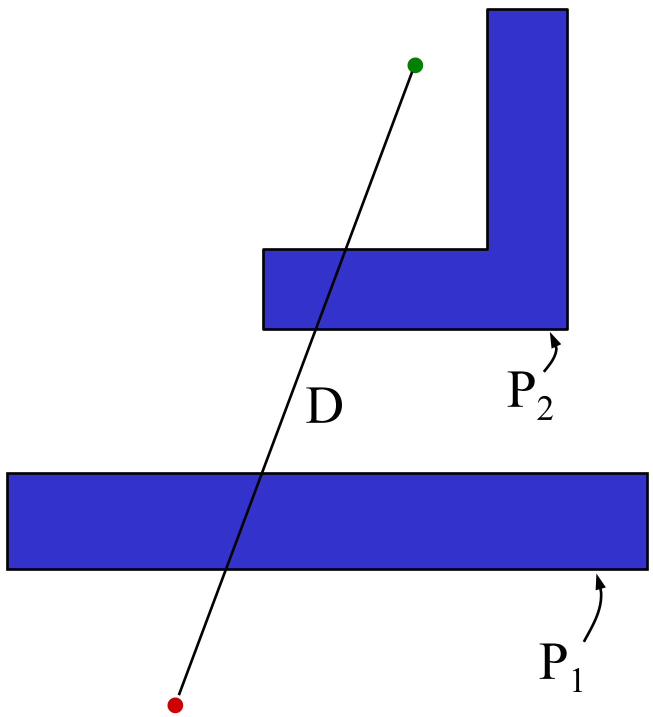
Lower and upper bounds?

Lower bound:

Upper bound:

Bug 1 analysis

Distance Traveled



What are bounds on the path length that the robot takes?

Available Information:

D = straight-line distance from start to goal

P_i = perimeter of the *i* th obstacle

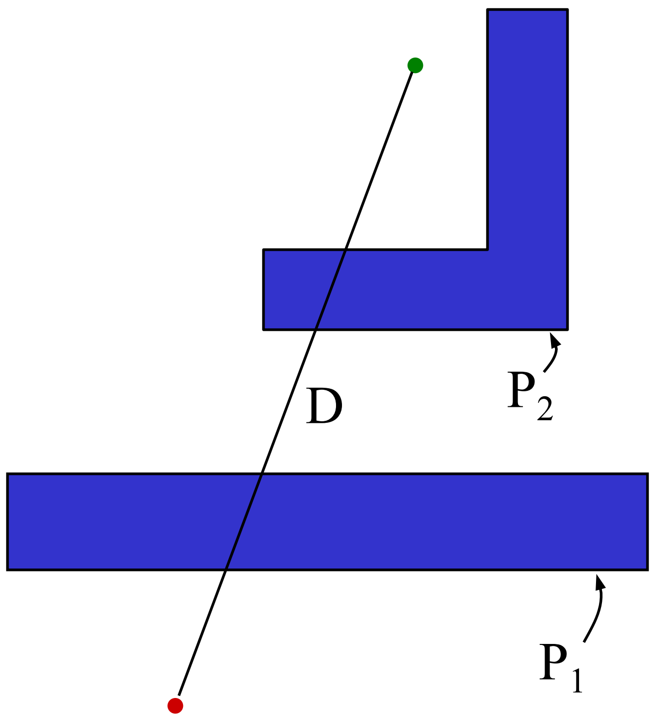
Lower and upper bounds?

Lower bound: D

Upper bound:

Bug 1 analysis

Distance Traveled



What are bounds on the path length that the robot takes?

Available Information:

D = straight-line distance from start to goal

P_i = perimeter of the *i* th obstacle

Lower and upper bounds?

Lower bound: D

Upper bound: $D + 1.5 \sum_i P_i$

How good a bound?

How good an algorithm?

Outline

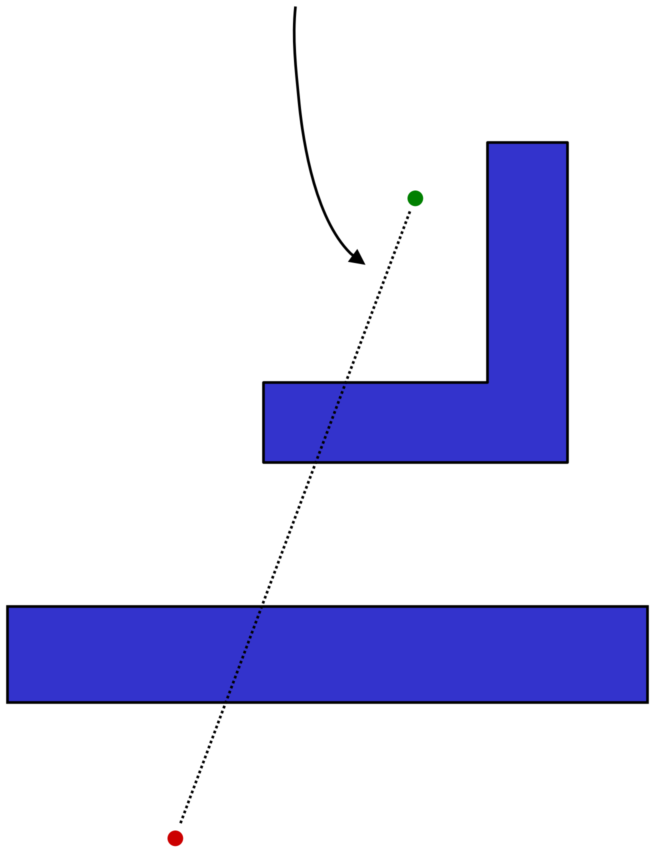
- Midterm Monday 20th Oct. 2008
- A better bug
- Tangent Bug
- Voronoi Graph
  - another roadmap path-planning method

Bug Mapping

A better bug?

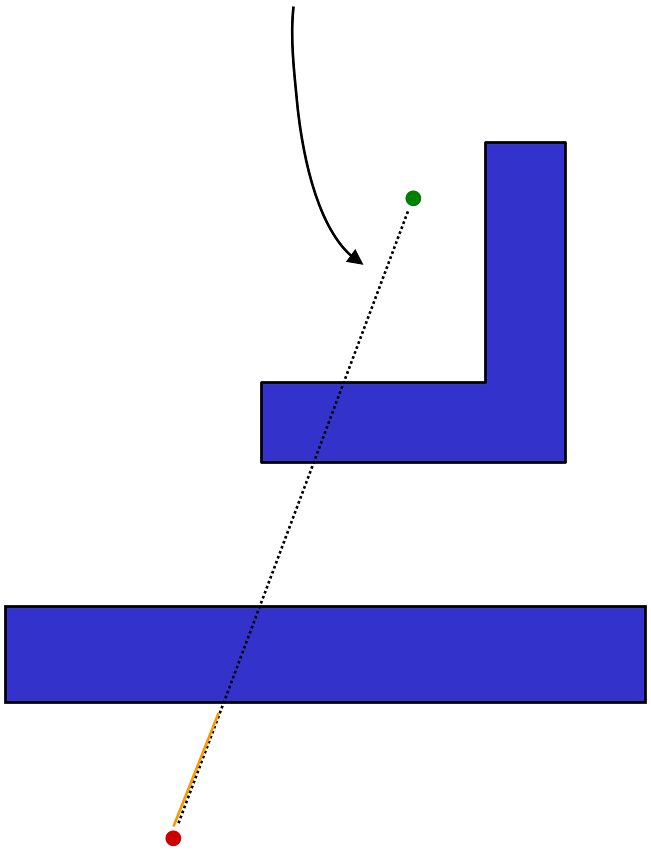
Call the line from the starting point to the goal the ***s-line***

“Bug 2” algorithm



A better bug?

Call the line from the starting point to the goal the ***s-line***

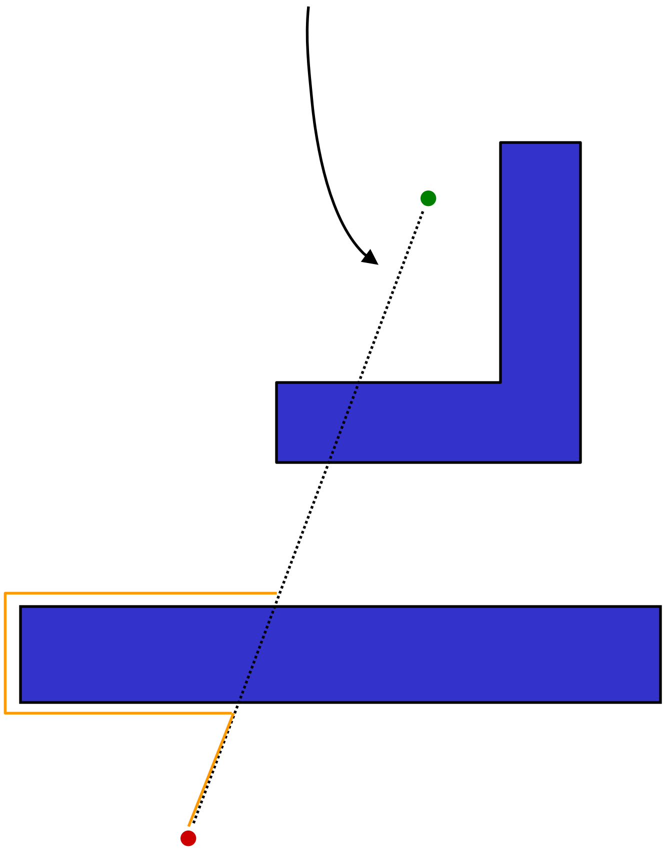


“Bug 2” algorithm

1) head toward goal on the *s-line*

A better bug?

Call the line from the starting point to the goal the ***s-line***

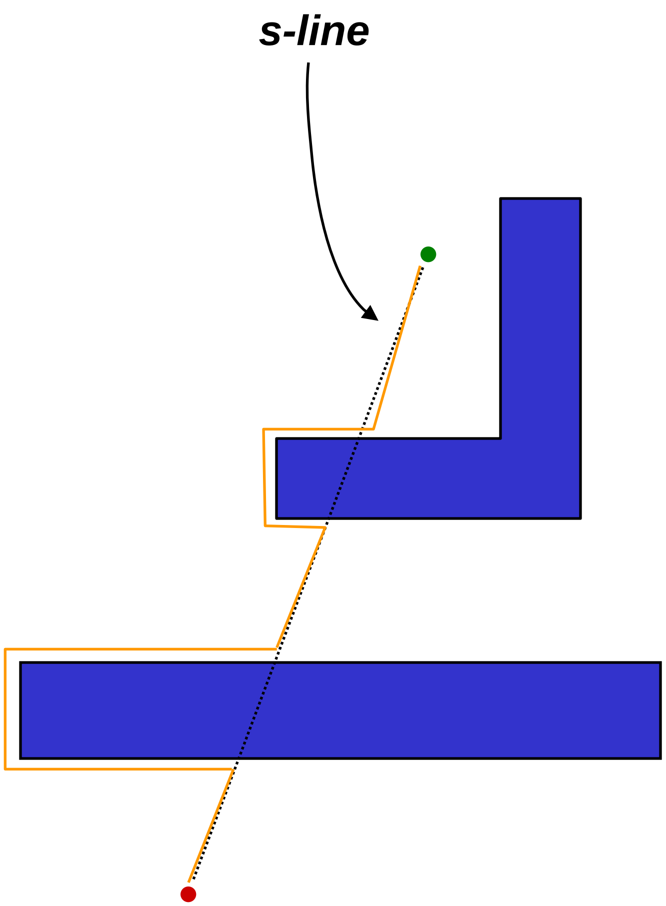


“Bug 2” algorithm

1) head toward goal on the *s-line*

2) if an obstacle is in the way, follow it until encountering the s-line again.

A better bug?



"Bug 2" algorithm

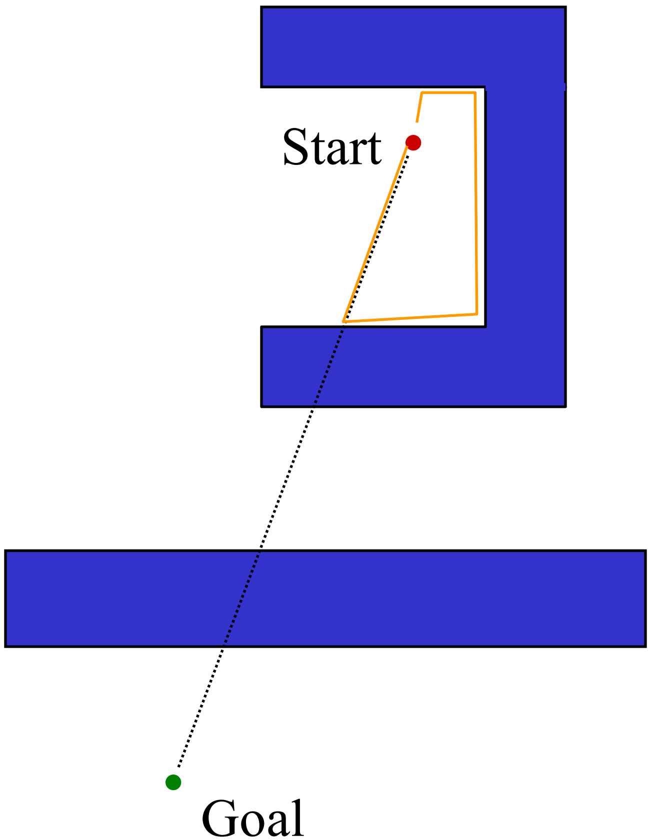
1) head toward goal on the *s-line*

2) if an obstacle is in the way, follow it until encountering the s-line again.

3) Leave the obstacle and continue toward the goal

OK ?

A better bug?



“Bug 2” algorithm

1) head toward goal on the *s-line*

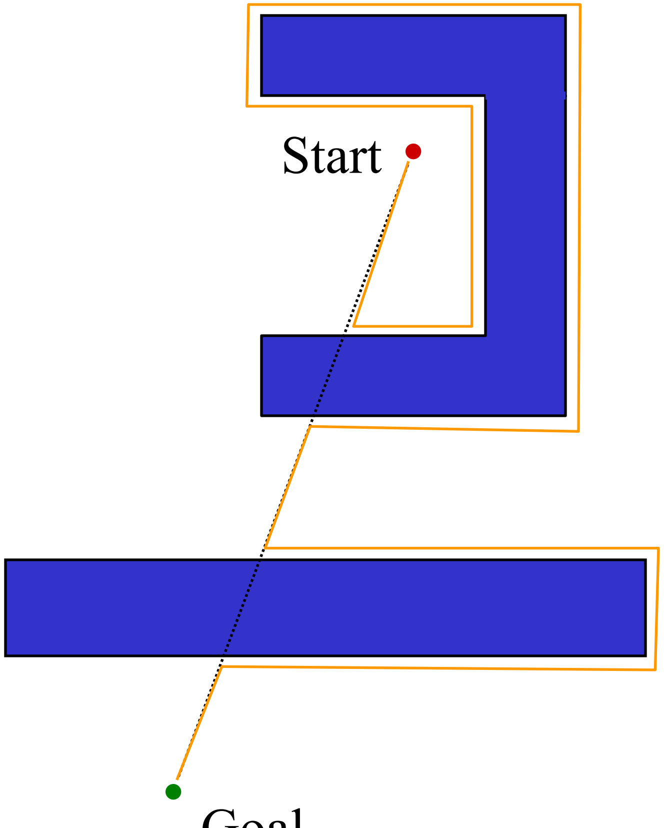
2) if an obstacle is in the way, follow it until encountering the s-line again *closer to the goal*.

3) Leave the obstacle and continue toward the goal

OK ?

Bug 2 analysis

Distance Traveled



What are bounds on the path length that the robot takes?

Available Information:

D = straight-line distance from start to goal

P_i = perimeter of the *i* th obstacle

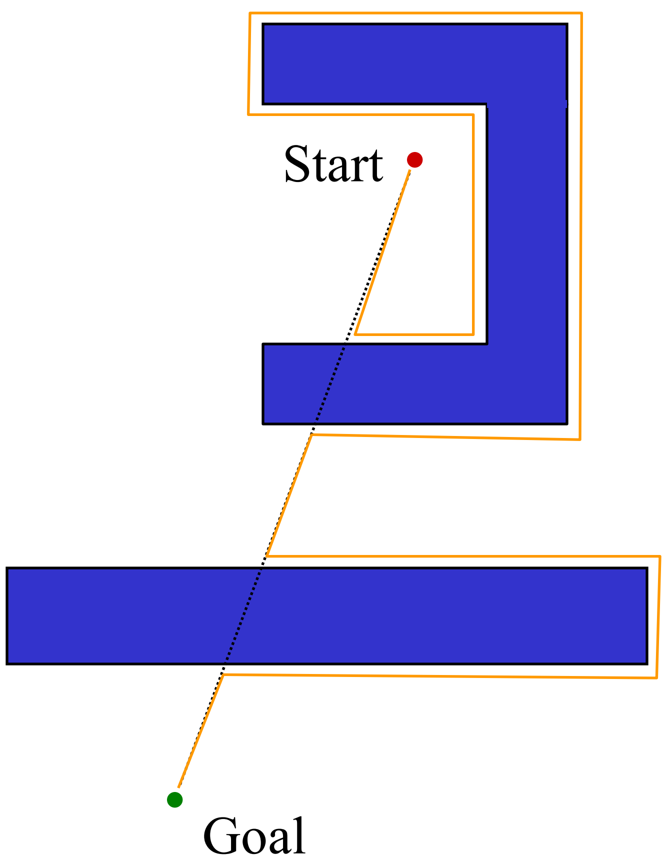
Lower and upper bounds?

Lower bound:

Upper bound:

Bug 2 analysis

Distance Traveled



What are bounds on the path length that the robot takes?

Available Information:

D = straight-line distance from start to goal

P_i = perimeter of the *i* th obstacle

N_i = number of s-line intersections with the *i* th obstacle

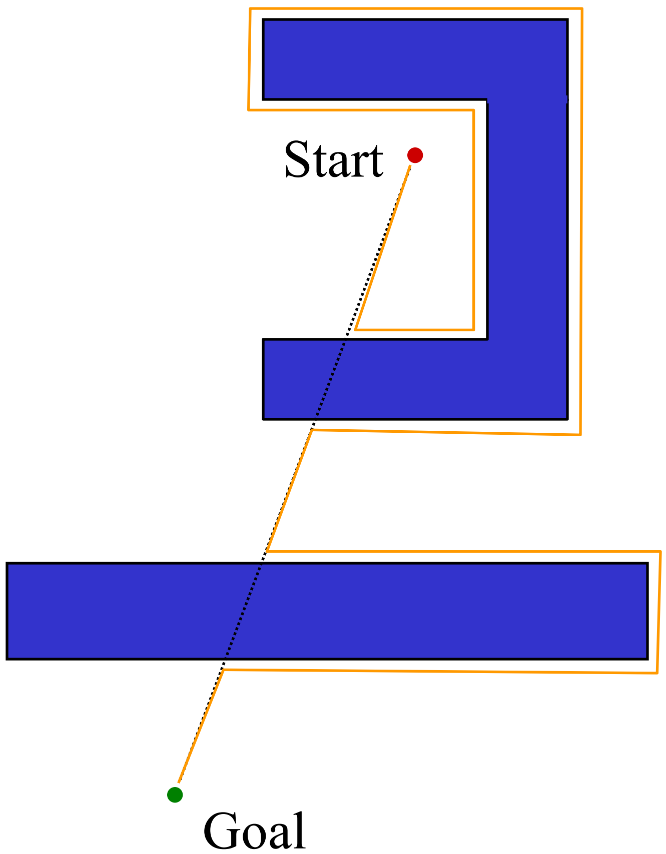
Lower and upper bounds?

Lower bound:

Upper bound:

Bug 2 analysis

Distance Traveled



What are bounds on the path length that the robot takes?

Available Information:

D = straight-line distance from start to goal

P_i = perimeter of the *i* th obstacle

N_i = number of s-line intersections with the *i* th obstacle

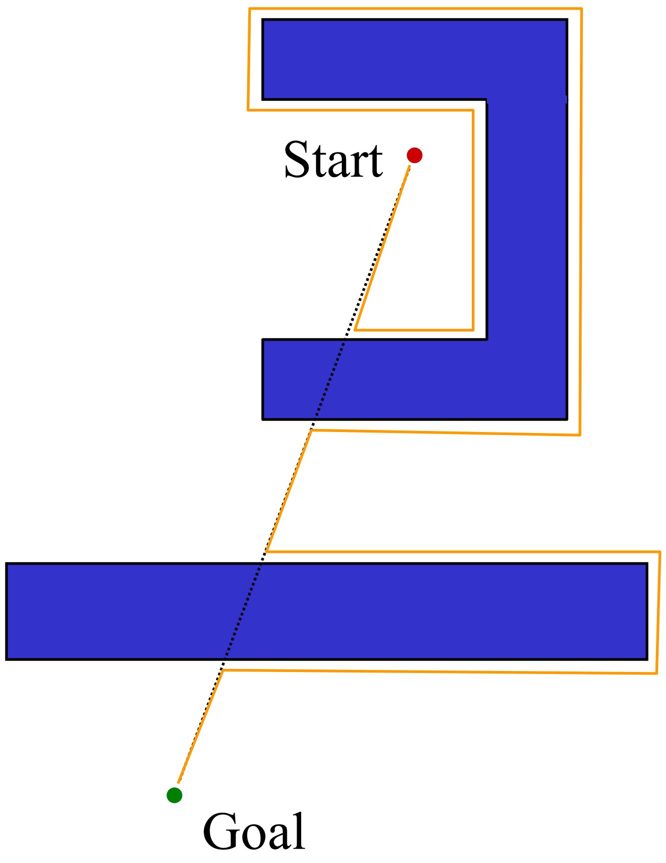
Lower and upper bounds?

Lower bound: D

Upper bound:

Bug 2 analysis

Distance Traveled



What are bounds on the path length that the robot takes?

Available Information:

D = straight-line distance from start to goal

P_i = perimeter of the *i* th obstacle

N_i = number of s-line intersections with the *i* th obstacle

Lower and upper bounds?

Lower bound: D

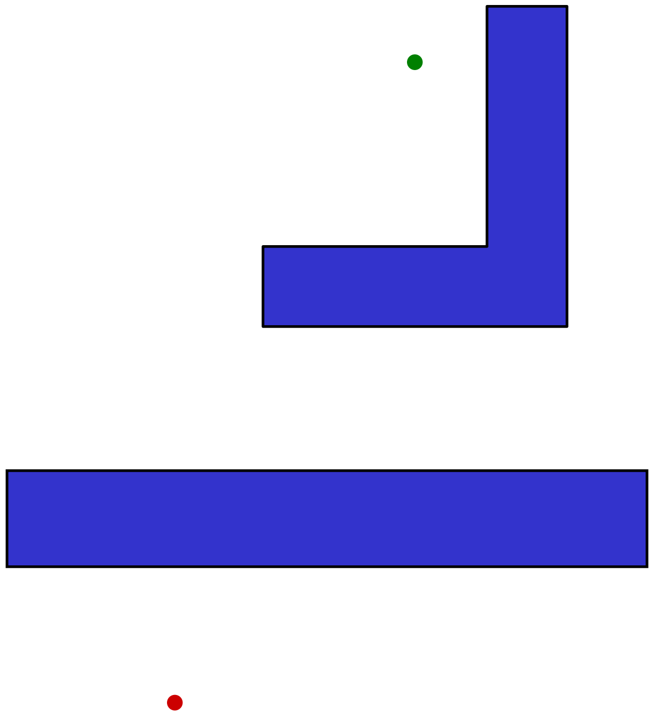
Upper bound: $D + 0.5 \sum_i N_i P_i$

head-to-head comparison

or thorax-to-thorax, perhaps

What are worlds in which Bug 2 does better than Bug 1 (and vice versa) ?

Bug 2 beats Bug 1	Bug 1 beats Bug 2

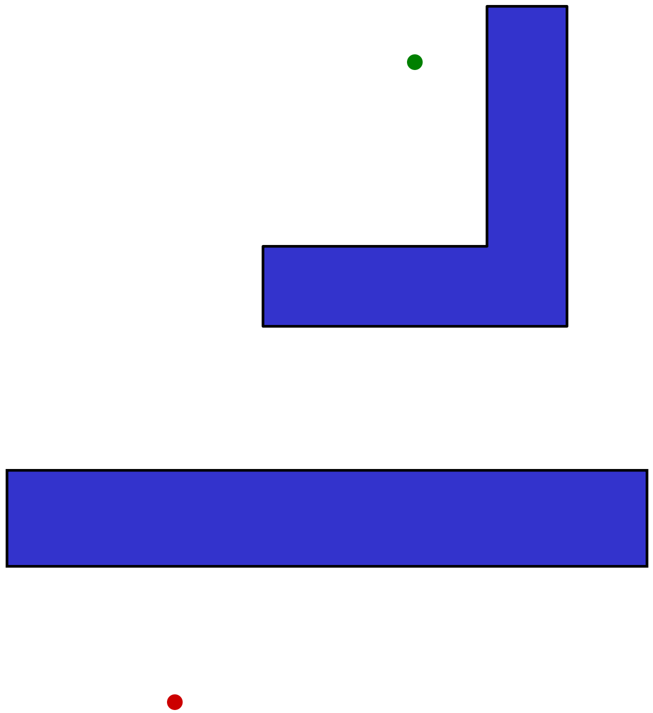


head-to-head comparison

or thorax-to-thorax, perhaps

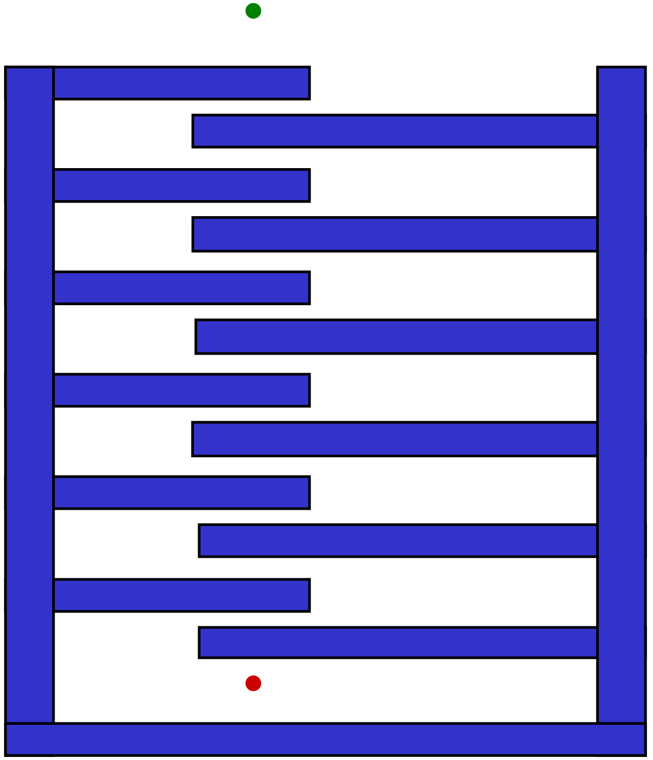
What are worlds in which Bug 2 does better than Bug 1 (and vice versa) ?

Bug 2 beats Bug 1



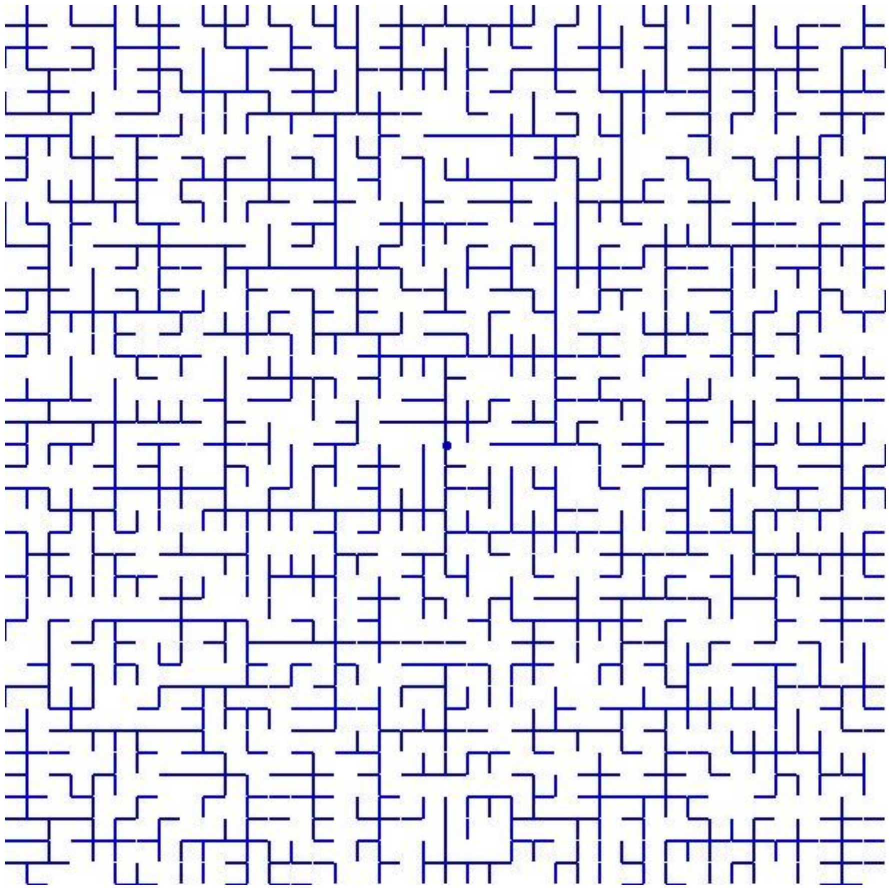
Bug 1 beats Bug 2

"zipper world"



Other bug-like algorithms

The Pledge maze-solving algorithm



1) Go to a wall

2) Keep the wall on your right

3) Continue until out of the maze

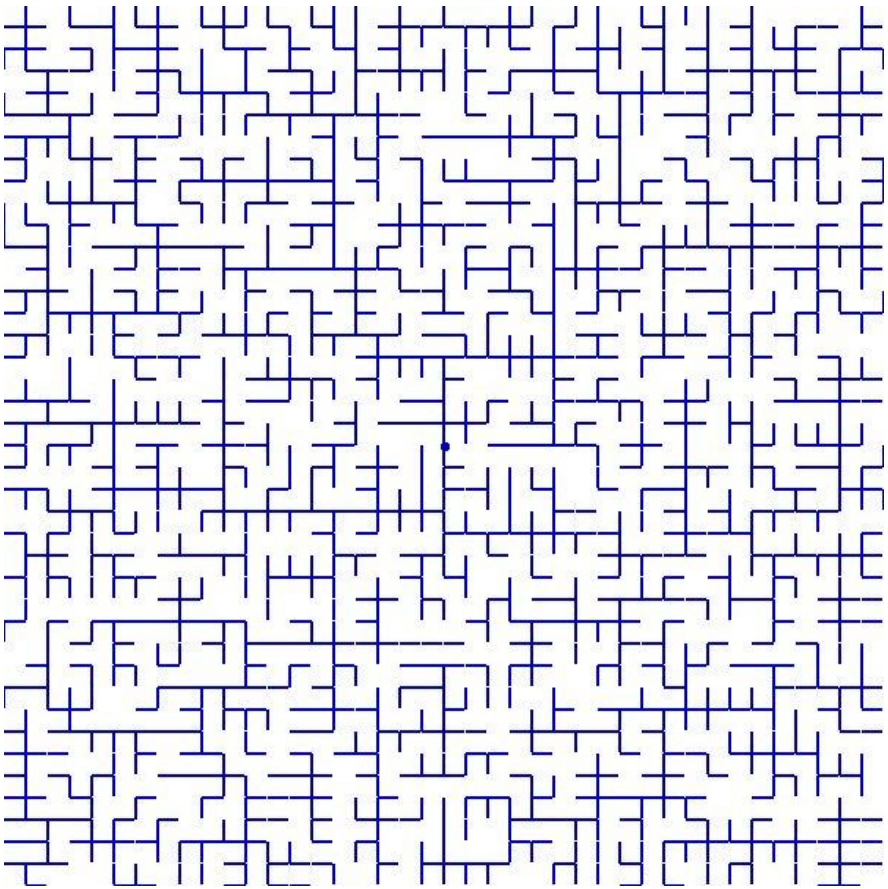
Other bug-like algorithms

The Pledge maze-solving algorithm

1) Go to a wall

2) Keep the wall on your right

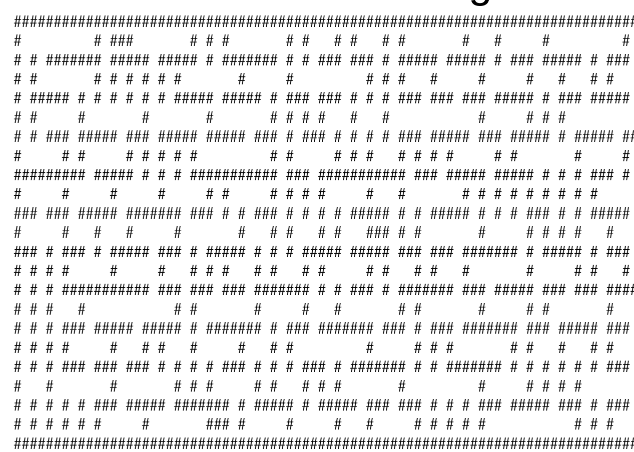
3) Continue until out of the maze



discretized RRT

```
int a[1817];main(z,p,q,r){for(p=80;q+p-80;p=2*a[p])
for(z=9;z--;)q=3&(r=time(0)+r*57)/7,q=q?q-1?q-2?1-
p%79?-1:0:p%79-77?1:0:p<1659?79:0:p>158?-
79:0,q?!a[p+q*2]?a[p+=a[p+=q]=q]=q:0:0;for(;q++-
1817;)printf(q%79?"%c":"%c\n"," #"[!a[q-1]]);}
```

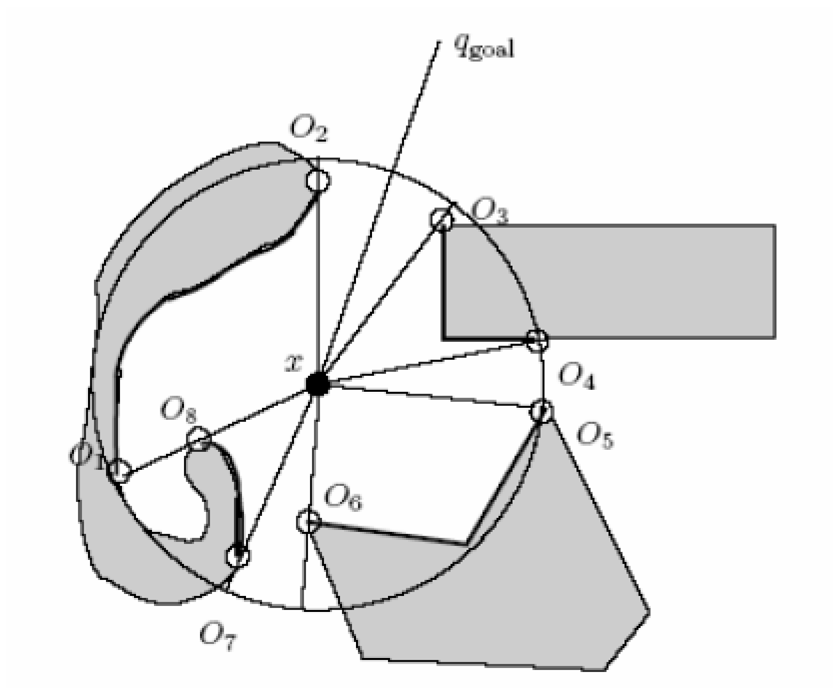
IOCCC random maze generator



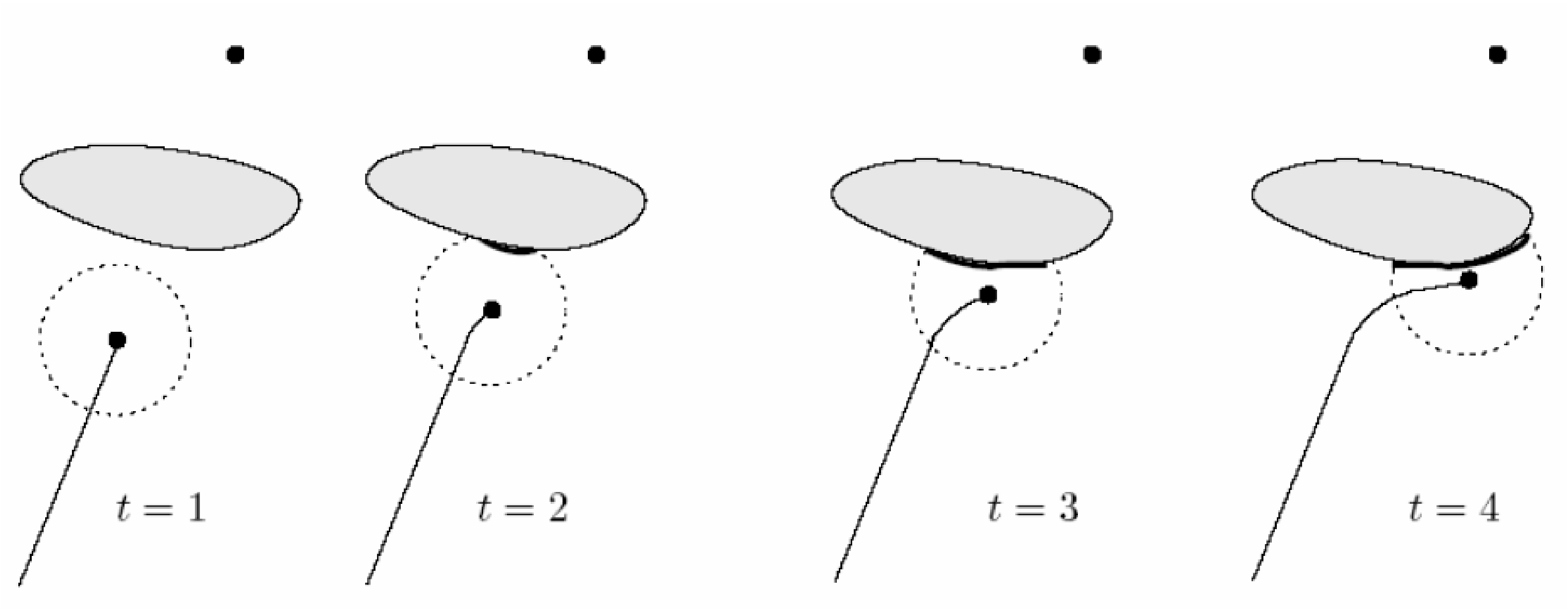
mazes of unusual origin

Tangent Bug

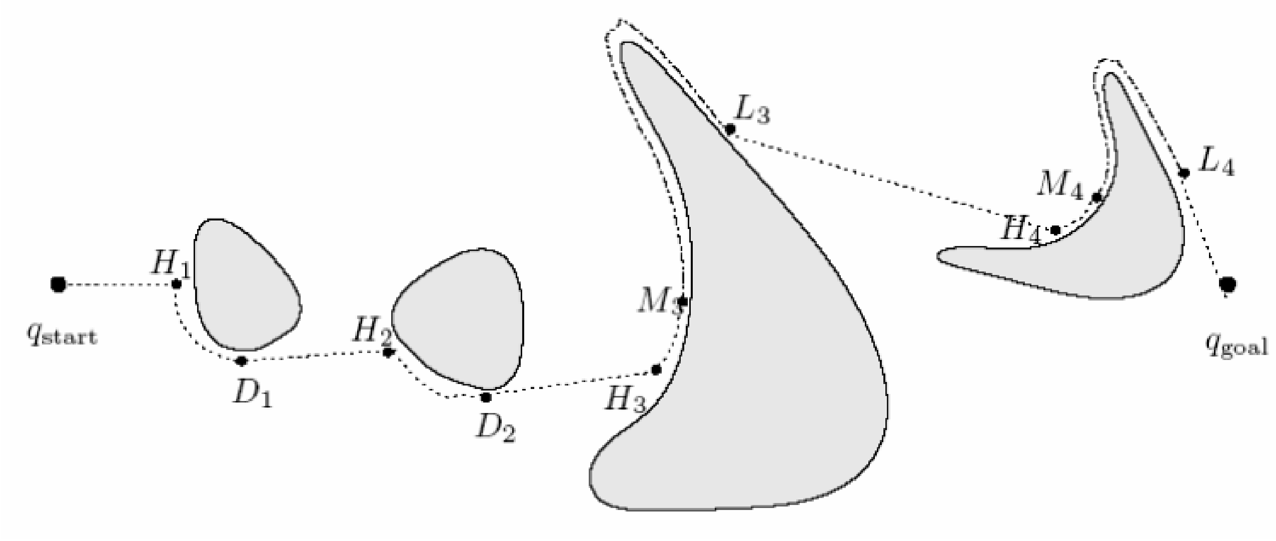
- Limited Range Sensor
- Tangent Bug relies on finding endpoints of finite, continues segments of the obstacles



Tangent Bug

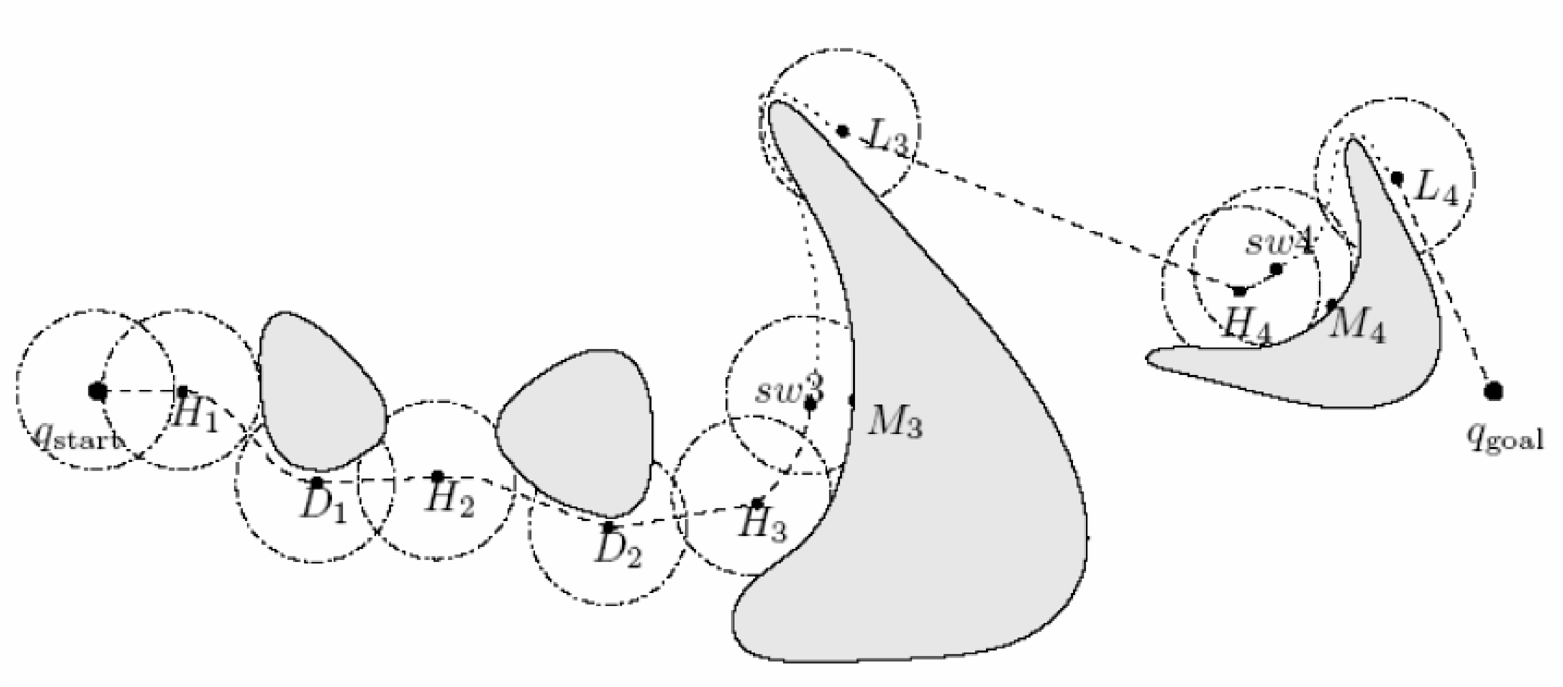


Contact Sensor Tangent Bug



1. Robot moves toward goal until it hits obstacle 1 at H1
2. Pretend there is an infinitely small sensor range and the direction which minimizes the heuristic is to the right
3. Keep following obstacle until robot can go toward obstacle again
4. Same situation with second obstacle
5. At third obstacle, the robot turned left until it could not increase heuristic
6. D_followed is distance between M3 and goal, d_reach is distance between robot and goal because sensing distance is zero

Limited Sensor Range Tangent-Bug



Infinite Sensor Range Tangent Bug