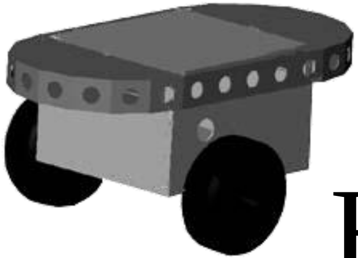
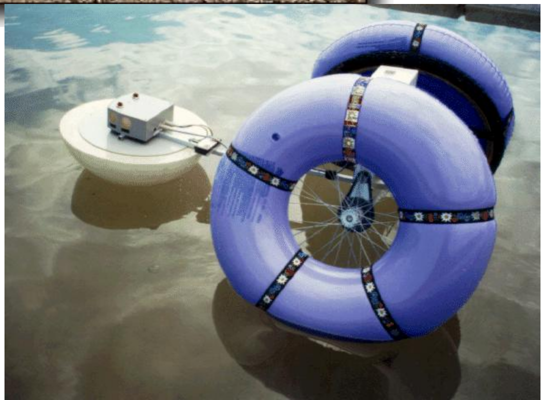
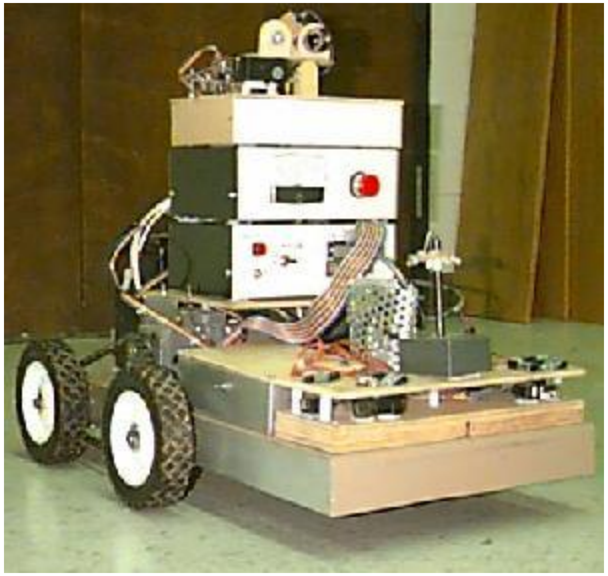
Coverage



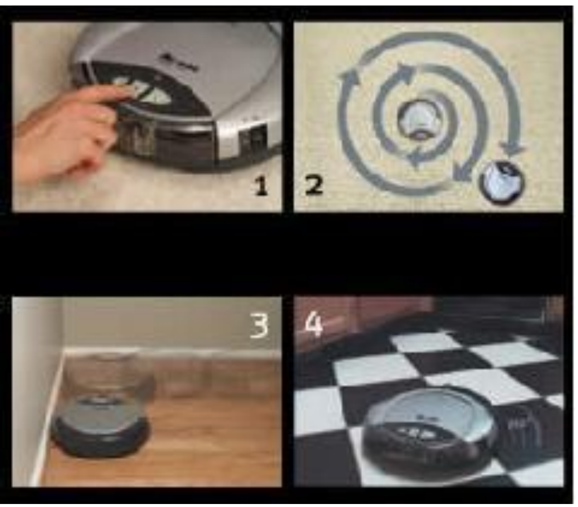
Motivation
Humanitarian Demining



Motivation
Lawn Mowing



Motivation
Vacuum Cleaning



Robotic Coverage

- More than 2 million Roombas sold!
- Automated Car Painting

Roomba Costumes

From: http://www.myroombud.com/

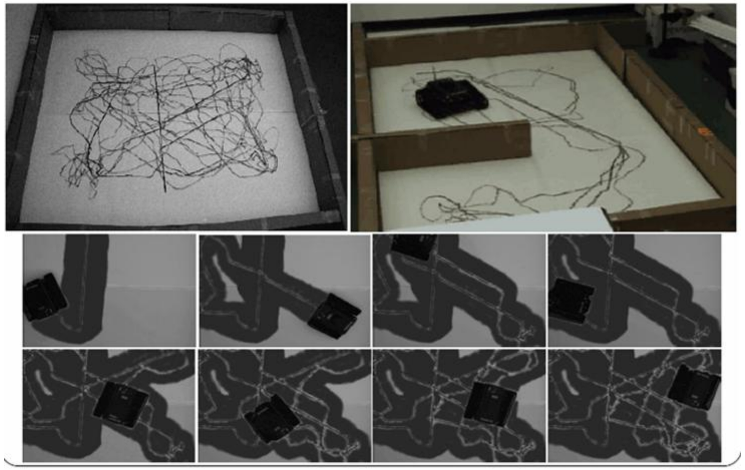
Coverage

- First Distinction
  - Deterministic **Demining**
  - Random **Vacuum Cleaning**
- Second Distinction
  - Complete
  - No Guarantee
- Third Distinction
  - Known Environment
  - Unknown Environment

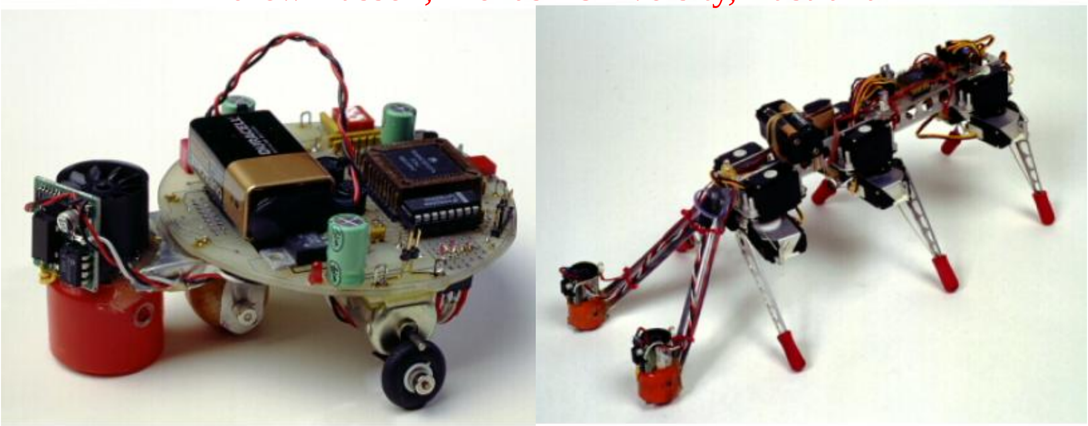
Non-Deterministic Coverage

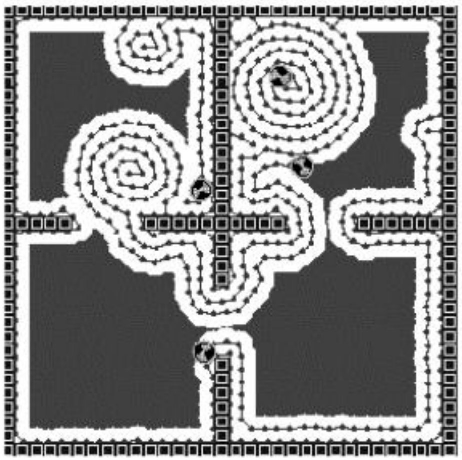
- Complete Random Walk
- Ant Robotics
  - Leave trail
  - Bias the behavior towards or away from the trails

S. Koenig Ant Robotics, terrain coverage



Andrew Russell, Monash University, Australia





Ant Robotics: I. Wagner, IBM & Technion

Deterministic Coverage

- Complete Algorithm
- Guarantees Complete Coverage

Cell-Decomposition Methods

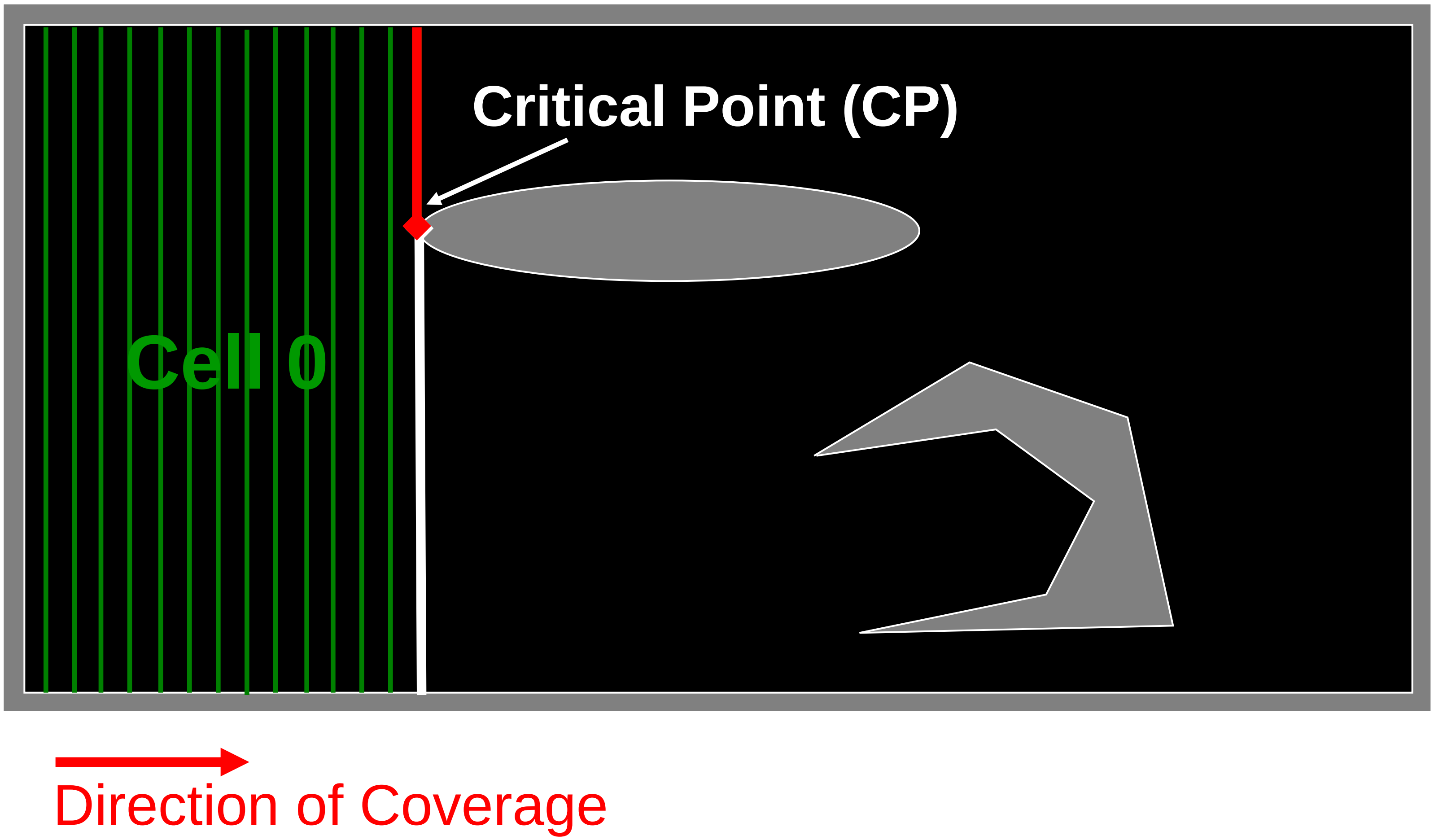
Two families of methods:

- Exact cell decomposition
  The free space F is represented by a collection of non-overlapping cells whose union is exactly F
  Examples: trapezoidal and cylindrical decompositions

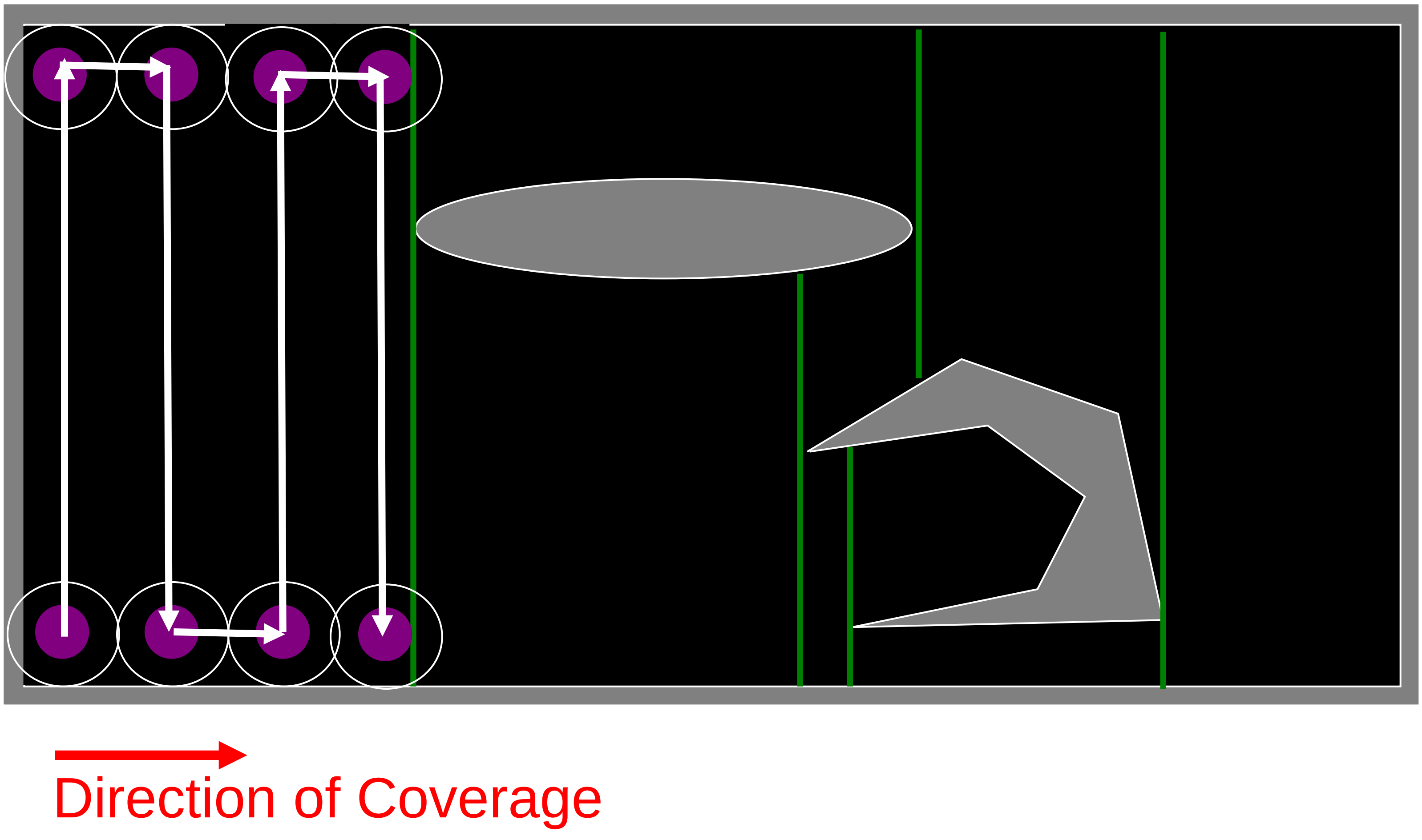
Boustrophedon Cellular Decomposition

The way of the Ox!

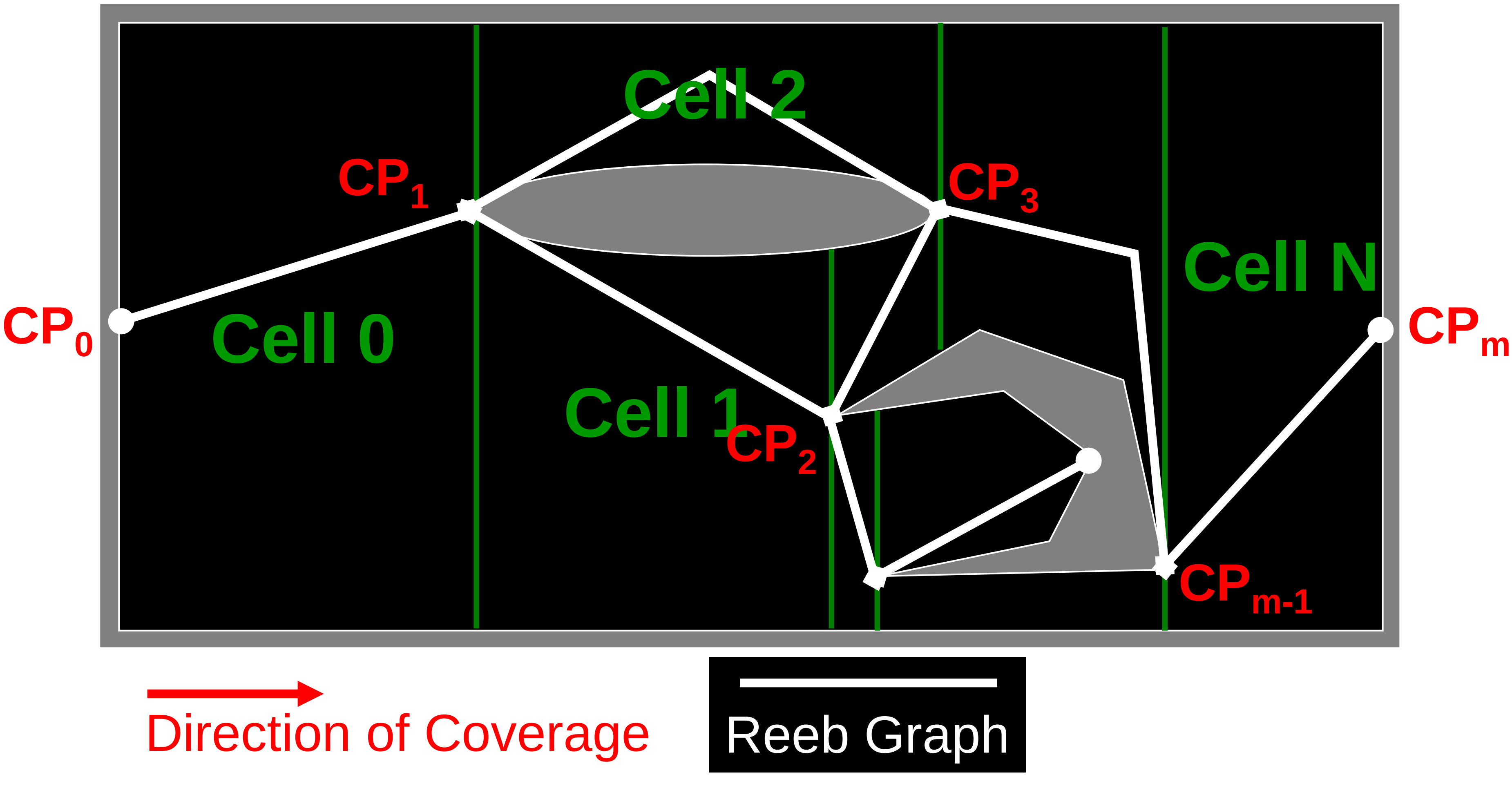
Cellular Decomposition



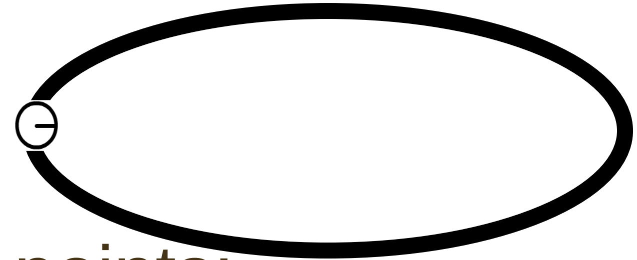
Single Cell Coverage



Cellular Decomposition

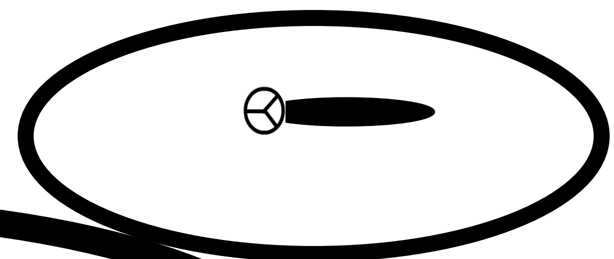


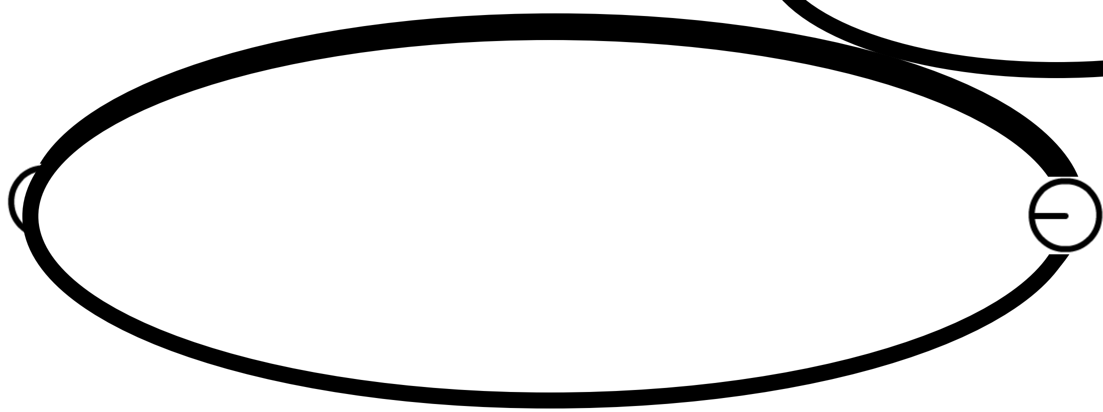
Critical Points



- There are four types of critical points:

  - Forward Concave critical point
  - Reverse Concave critical point
  - Reverse Convex critical point
  - Forward Convex critical point





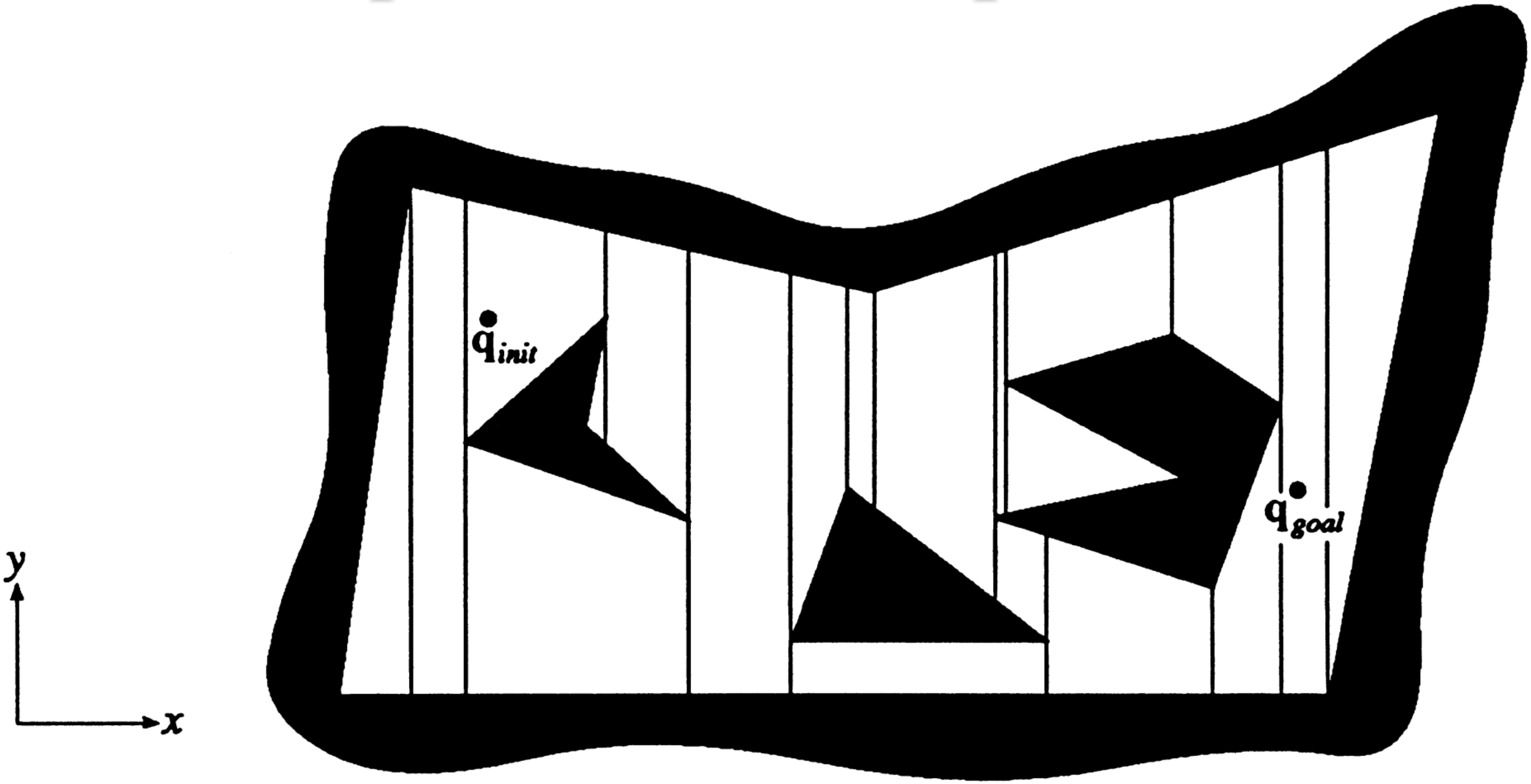
Direction of Coverage

Demining in Action (almost)

Cell decomposition for Path Planning

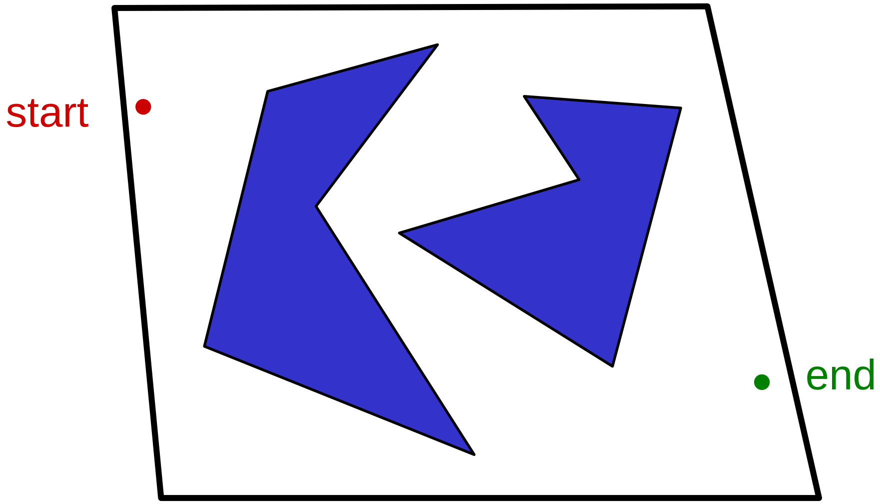
- Decompose the free space into simple cells and represent the connectivity of the free space by the adjacency graph of these cells

Trapezoidal decomposition



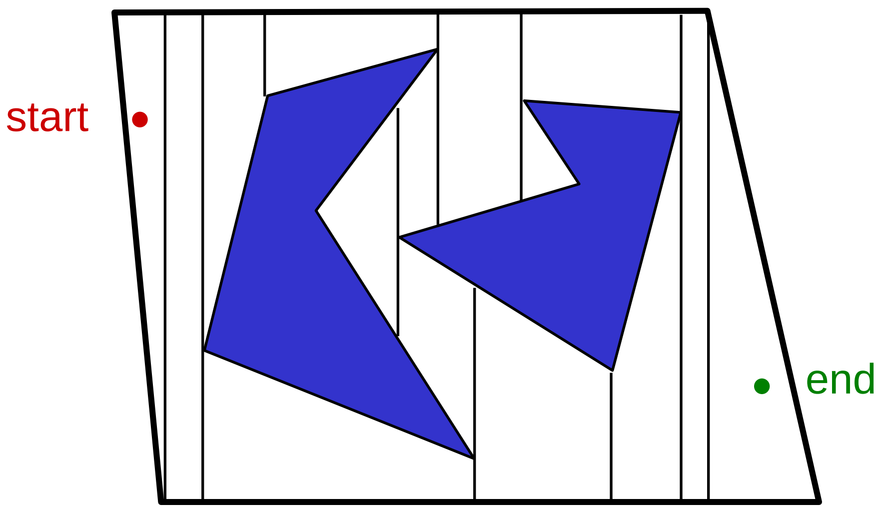
Spatial decompositions

Dividing free space into pieces and using those...



Spatial decompositions

Dividing free space into pieces and using those...



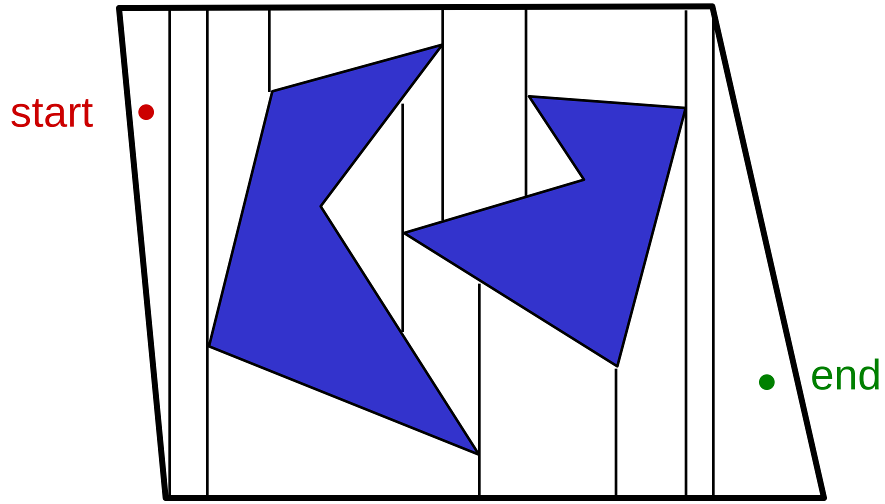
Running time?

Exact cell decomposition

sweepline algorithm

Spatial decompositions

Dividing free space into pieces and using those...



Running time?

Path?

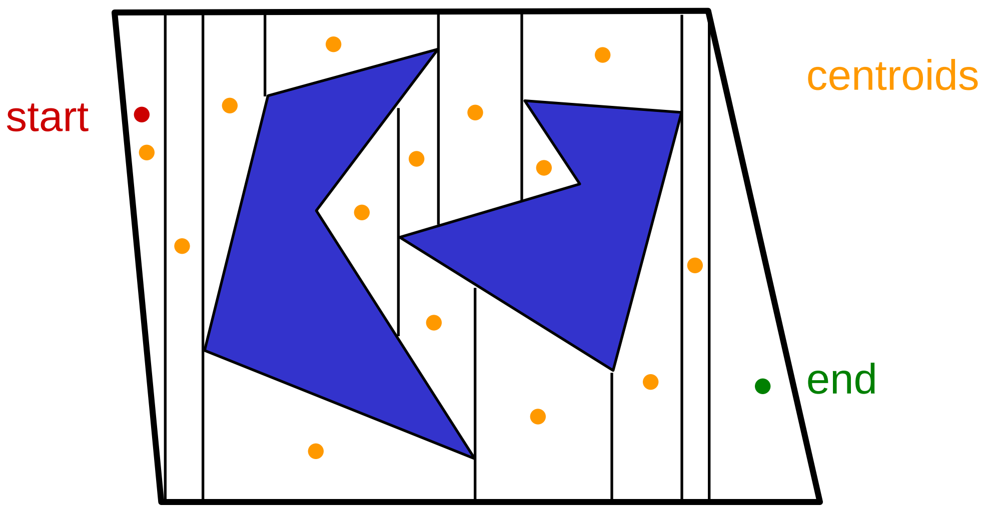
Exact cell decomposition

sweepline algorithm

O(N log(N))

Spatial decompositions

Dividing free space into pieces and using those...



Running time?

O(N log(N))

Path?

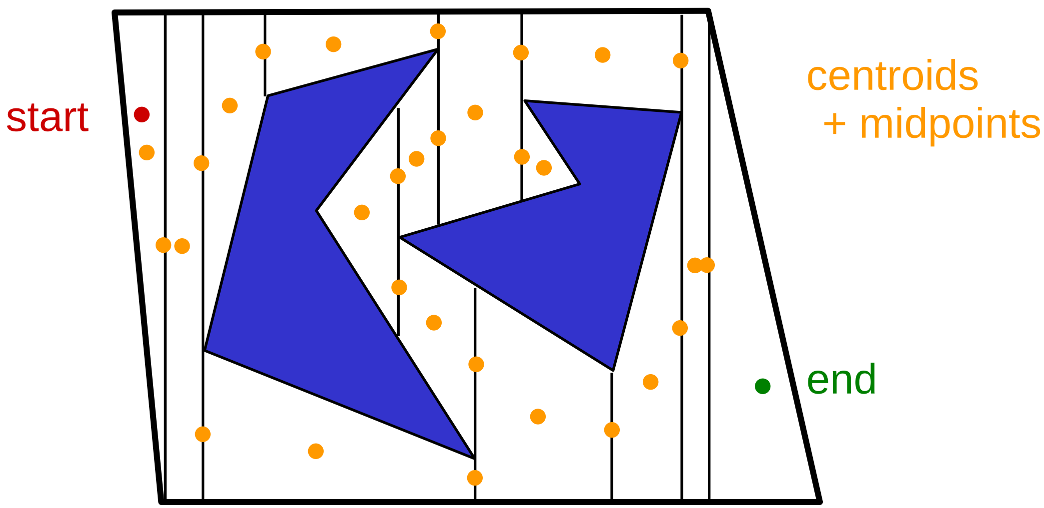
via centroids

Exact cell decomposition

sweepline algorithm

Spatial decompositions

Dividing free space into pieces and using those...



Running time?

Path?

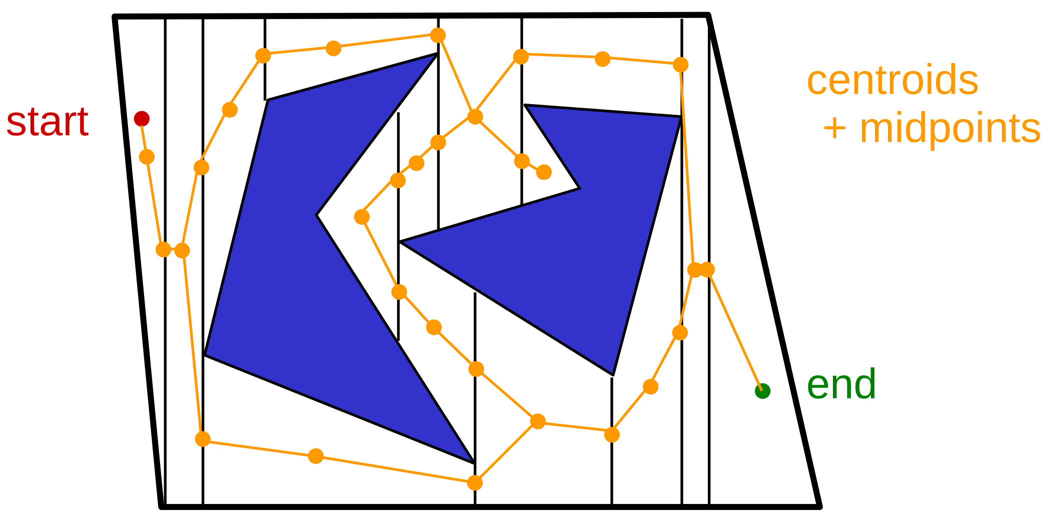
Exact cell decomposition
sweepline algorithm

O(N log(N))

via centroids
+ edge midpoints

Spatial decompositions

Dividing free space into pieces and using those...



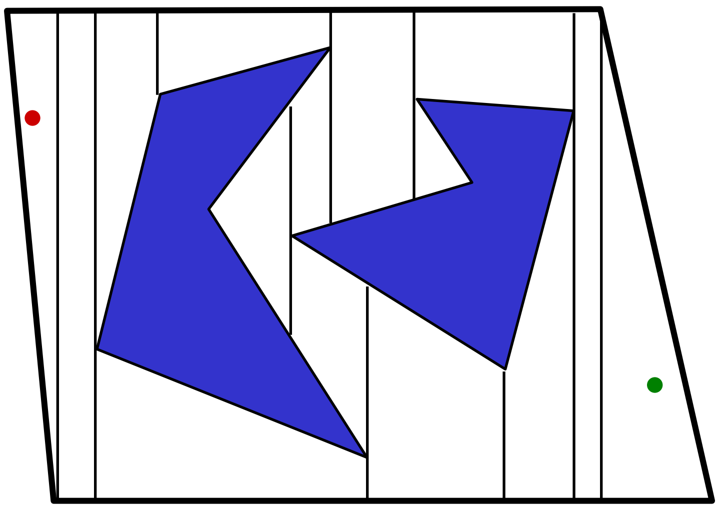
Exact cell decomposition

sweepline algorithm

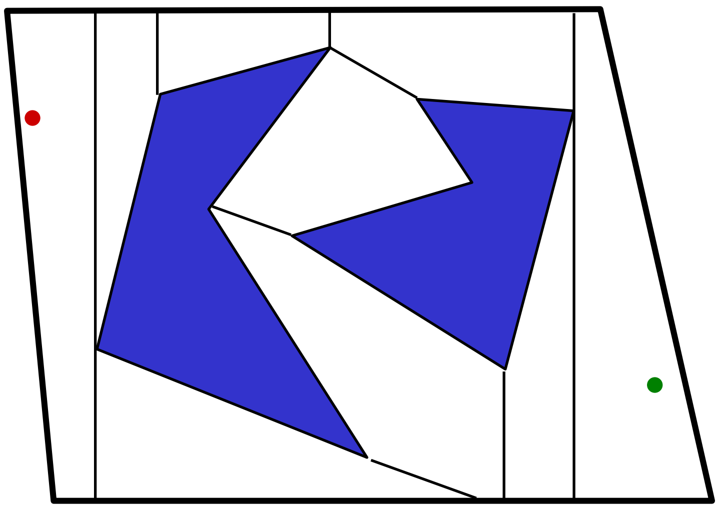
Running time?	Path?	Why?
O(N log(N))	via centroids + edge midpoints + graph search	why else?

Optimality

Obtaining the *minimum* number of convex cells is NP-complete.



15 cells



9 cells

Trapezoidal decomposition is exact and complete, but not optimal -- even among convex subdivisions.

there may be more detail in the world than the task needs to worry about...

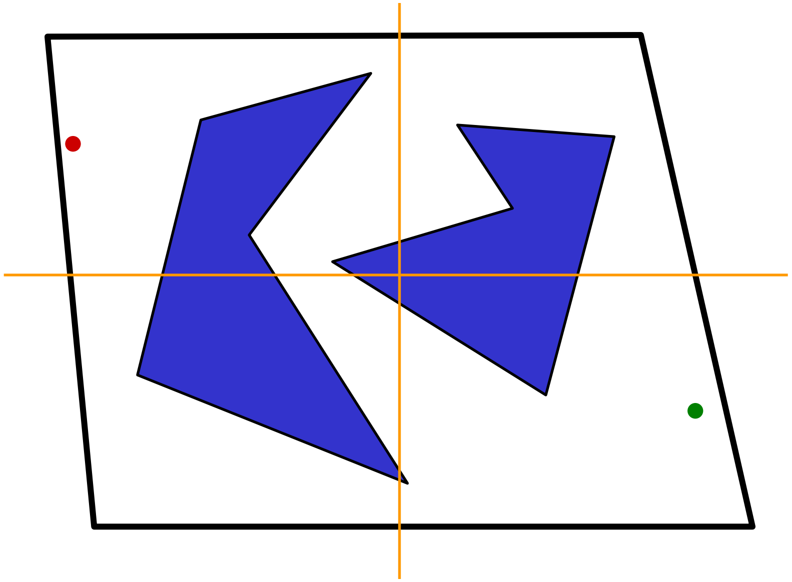
Cell-Decomposition Methods

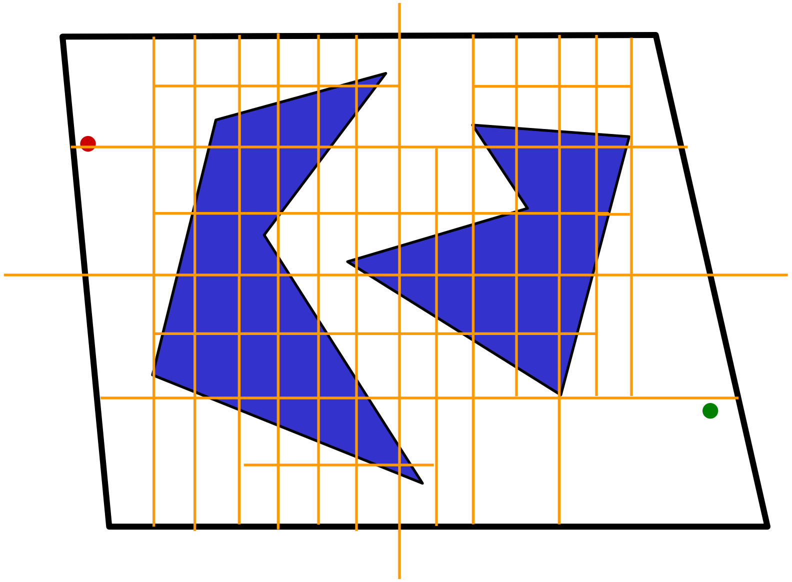
Two families of methods:

- Exact cell decomposition
- Approximate cell decomposition
  F is represented by a collection of non-overlapping cells whose union is contained in F
  Examples: quadtree, octree, 2^n-tree

further decomposing...

Approximate cell decomposition



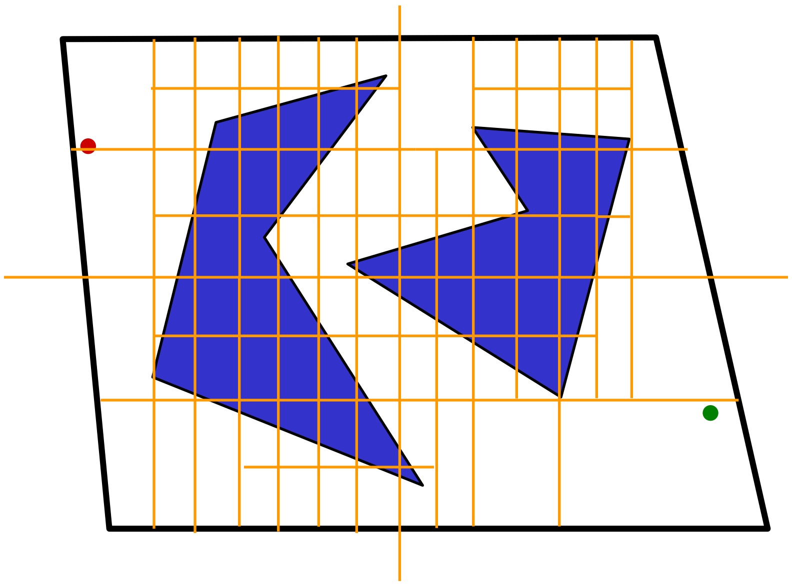


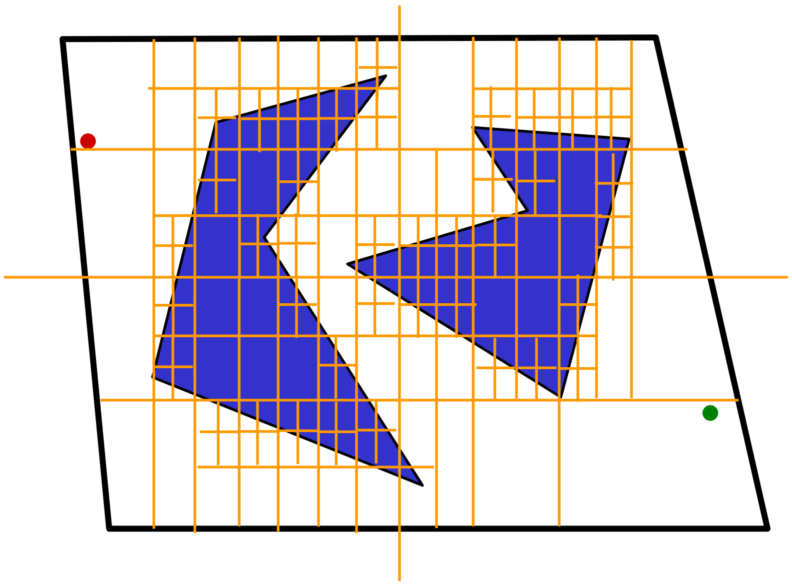
Quadtree:

recursively subdivides each *mixed* obstacle/free (sub)region into four quarters...

further decomposing...

Approximate cell decomposition



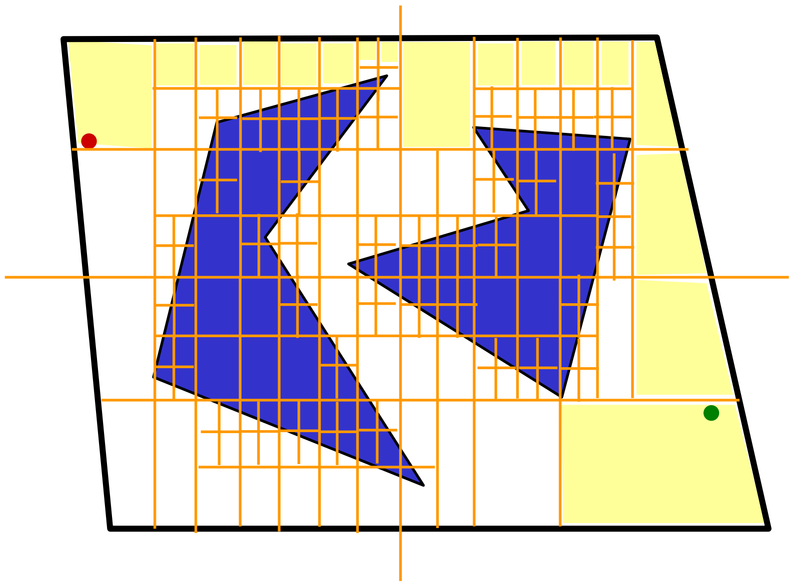


Quadtree:

recursively subdivides each *mixed* obstacle/free (sub)region into four quarters...

further decomposing...

Approximate cell decomposition

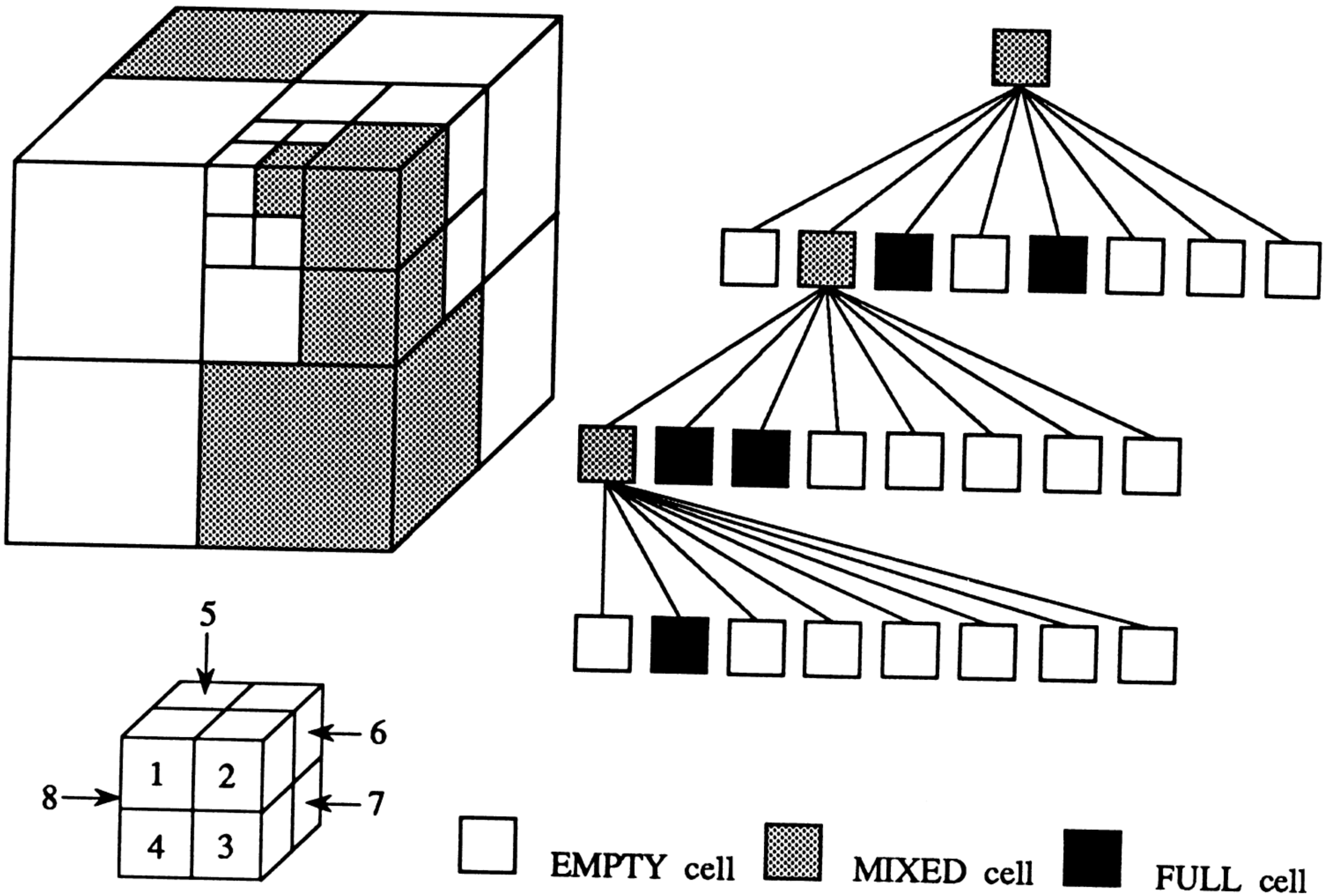


Quadtree

Again, use a graph-search algorithm to find a path from the start to goal

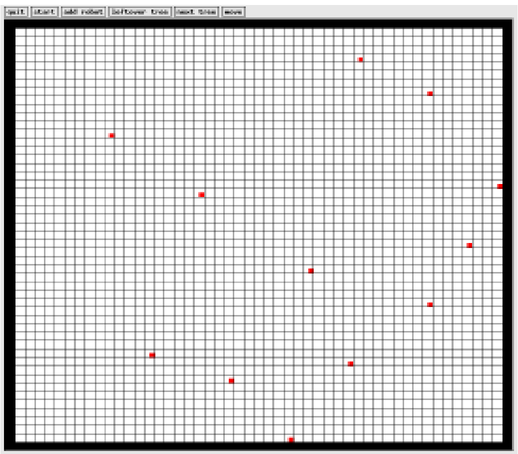
is this a **complete** path-planning algorithm?
i.e., does it find a path when one exists ?

Octree Decomposition

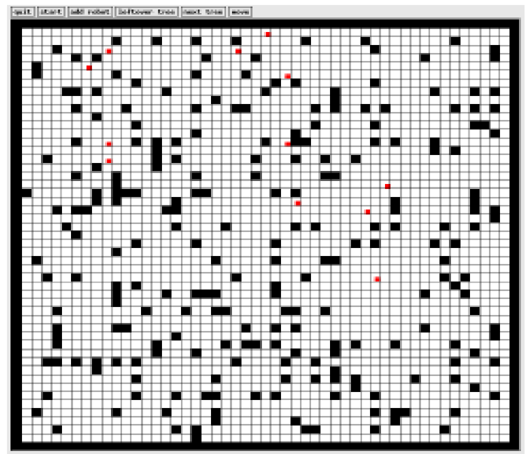


Coverage of Known Worlds

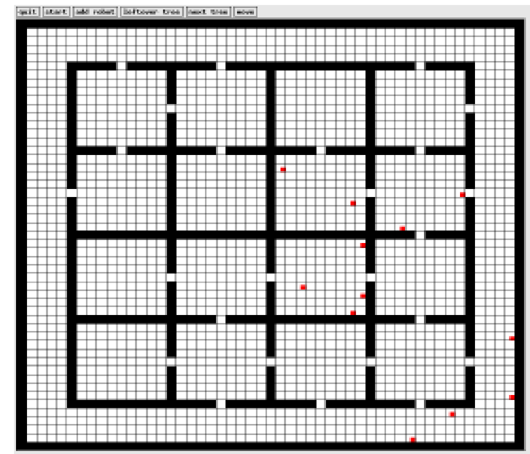
Empty Terrain



Outdoor-Like Terrain

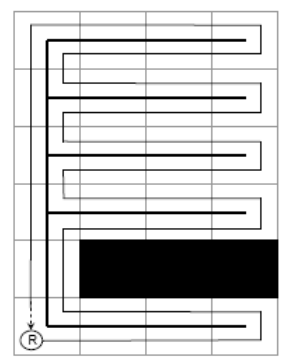


Indoor-Like Terrain

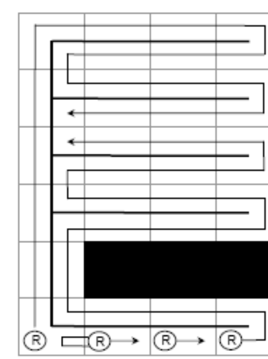


From: X. Zheng and S. Koenig. Robot Coverage of Terrain with Non-Uniform Traversability. In Proc. of the IEEE Int. Conf. on Intelligent Robots and Systems (IROS), pg. 3757-3764, 2007

STC
cover time = 682
cover and return time = 688



MSTC
cover time = 332
cover and return time = 394



Multi-Robot Complete Coverage

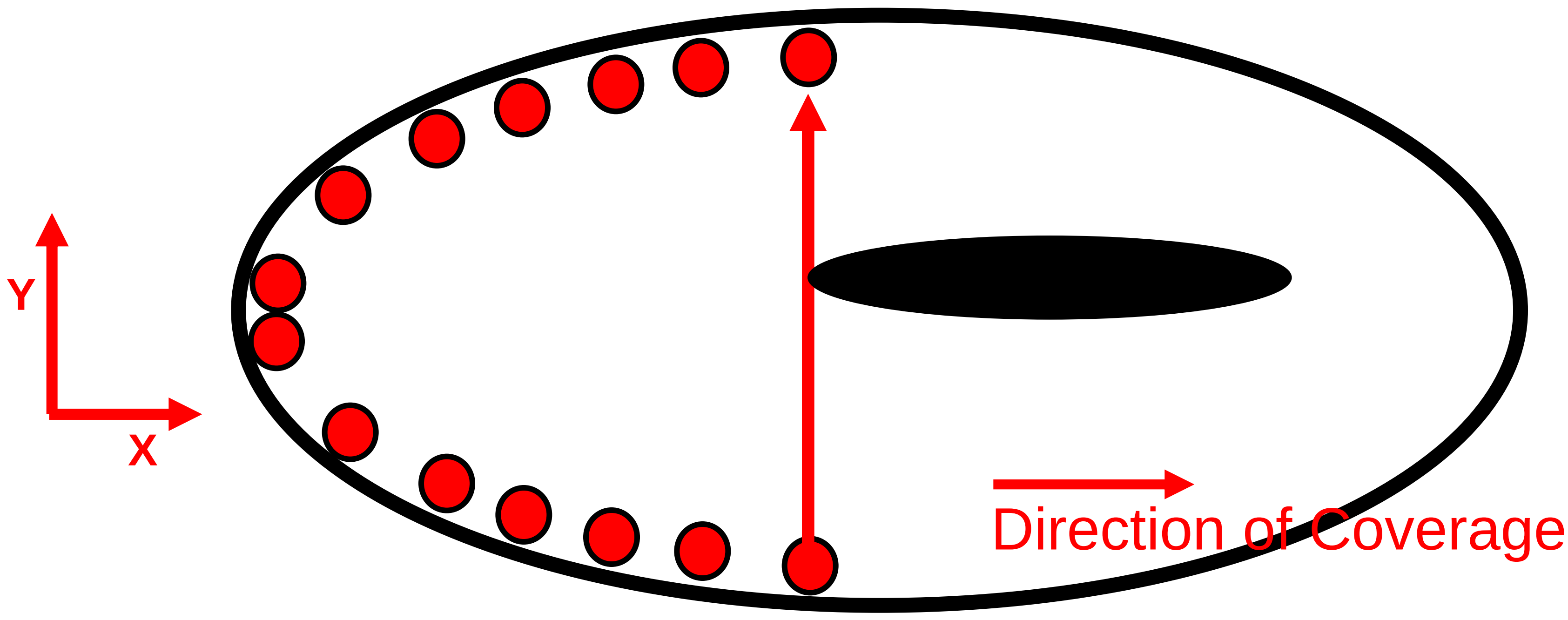
- Multiple Robots:
  - Efficiency
  - Robustness
  - Higher Complexity
- Inter-Robot Communication Abilities
- Guarantee of Complete Coverage

Multi Robot Complete Coverage Limited Communication: Main Ideas

- Communication is limited to Line of Sight
- Coverage of a single cell
  - Robots have two roles:
    - Explorers
    - Coverers
- Team coordination for complete coverage of the environment
  - Limited communication
  - Deterministic approach
  - Team splits only once

Single Cell Coverage

- Each team of *N* robots has:
  - *2* explorers, *N-2* coverers
- The explorers trace the top and bottom border of the Cell maintaining the same X-coordinate until the Line of Sight is broken (i.e. a critical point is detected)

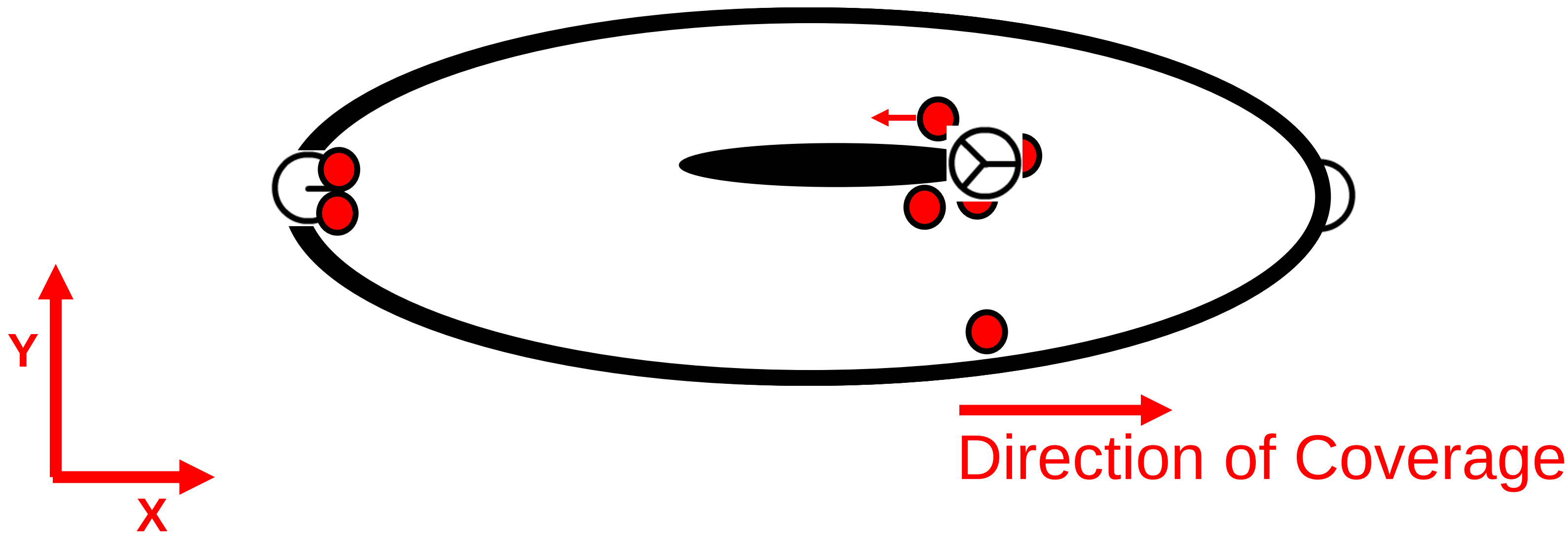


Single Cell Coverage

- Each team of *N* robots has:
  - *2* explorers, *N-2* coverers
- The explorers trace the top and bottom border of the Cell maintaining the same X-coordinate until the Line of Sight is broken (i.e. a critical point is detected)
- The coverers use an up-and-down motion to cover the interior of the cell

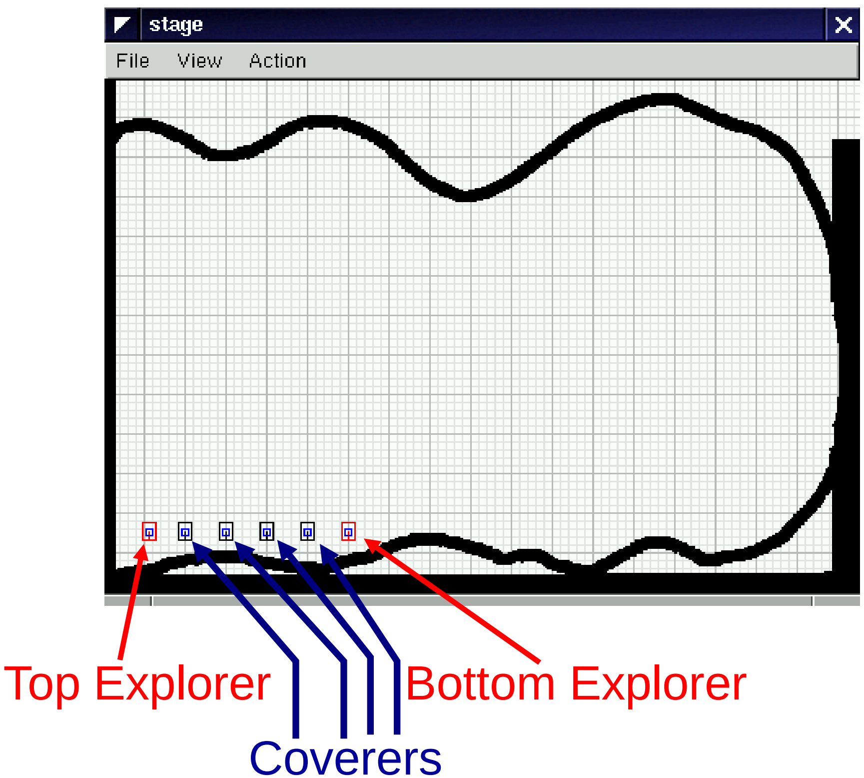
Critical Point Detection

- The explorers are able to detect all critical points:
  - Forward Concave CP (encountered only at start-up)
  - Reverse Concave CP (explorers approach each other)
  - Reverse Convex CP (Line of Sight breaks)
  - Forward Convex CP (Explorer reverses direction)

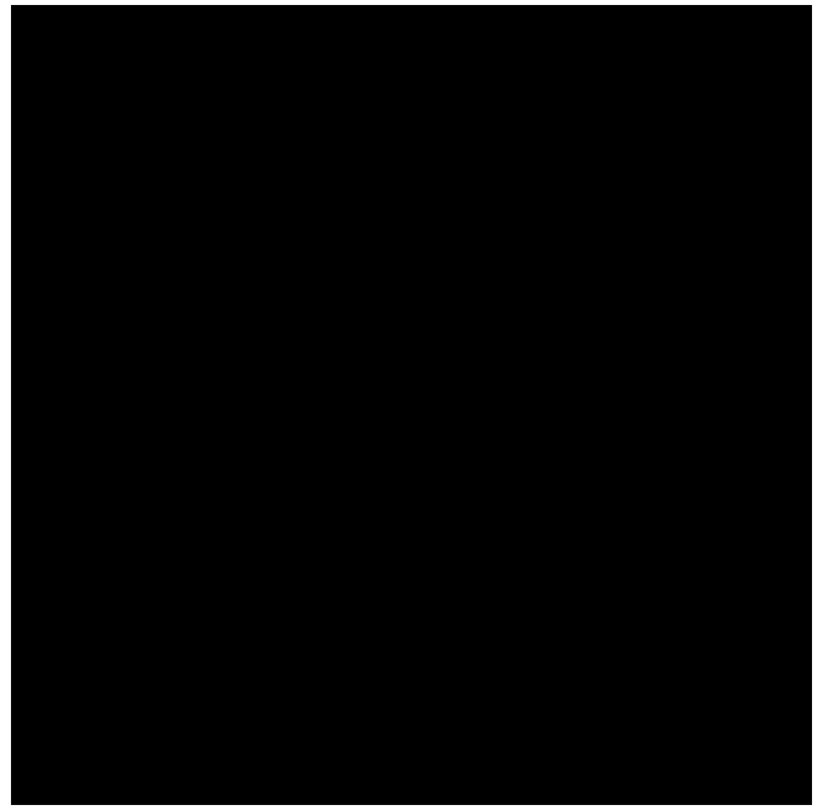


Single Cell Coverage

Reverse Concave Critical Point

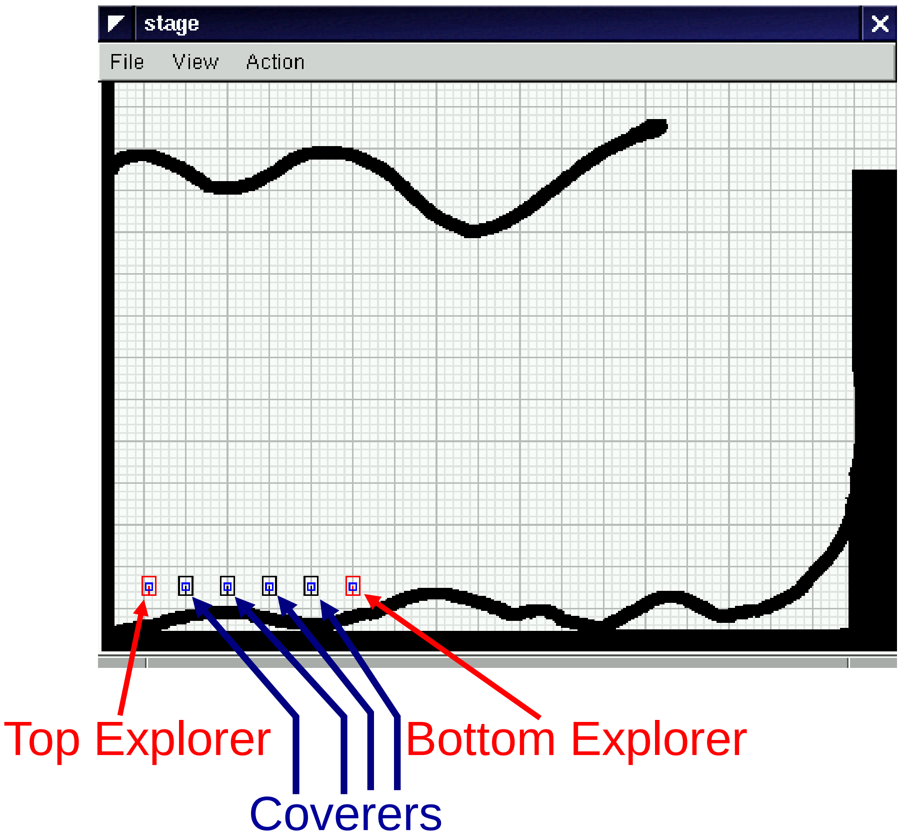


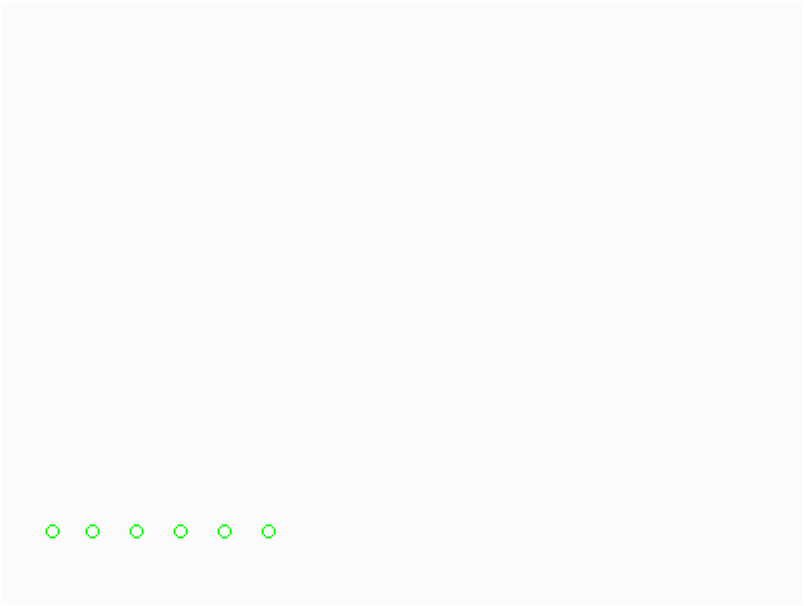
The circles represent the robot position not the sensor footprint.



Single Cell Coverage

Forward Convex Critical Point





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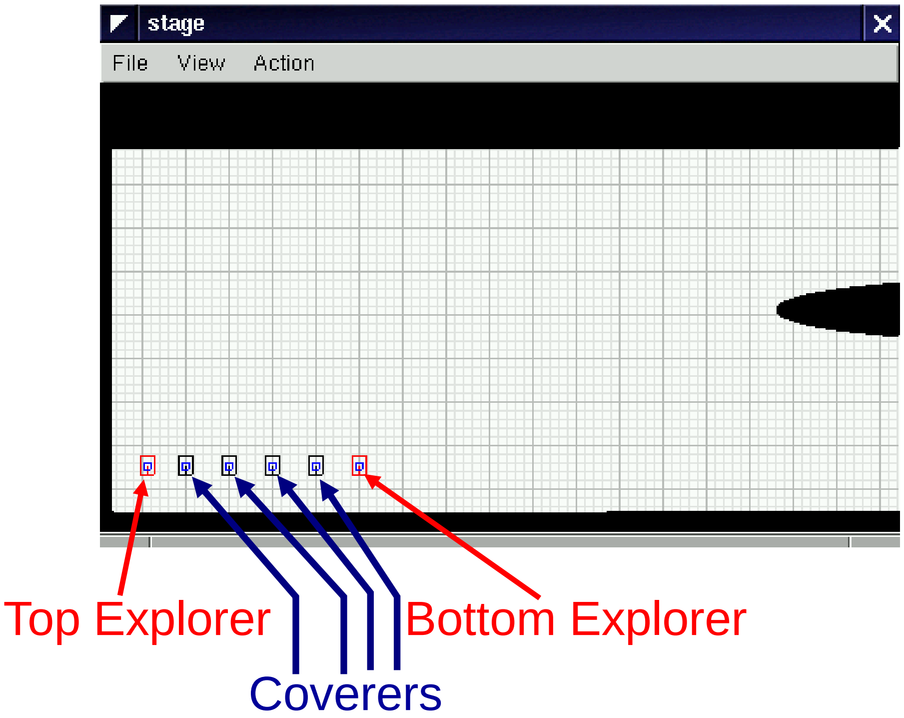
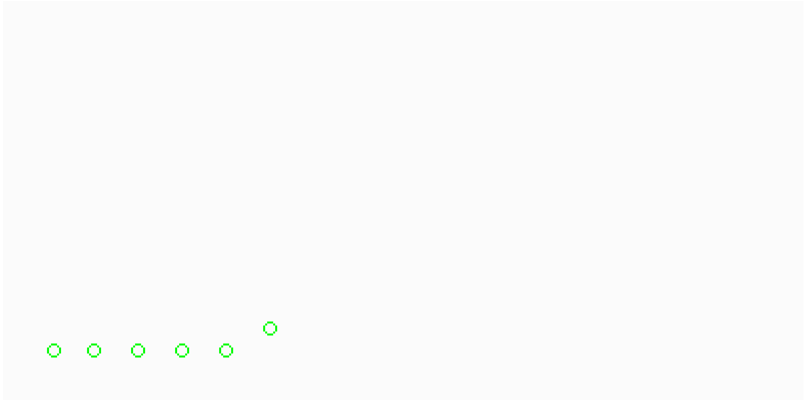
Single Cell Coverage

Reverse Convex Critical Point



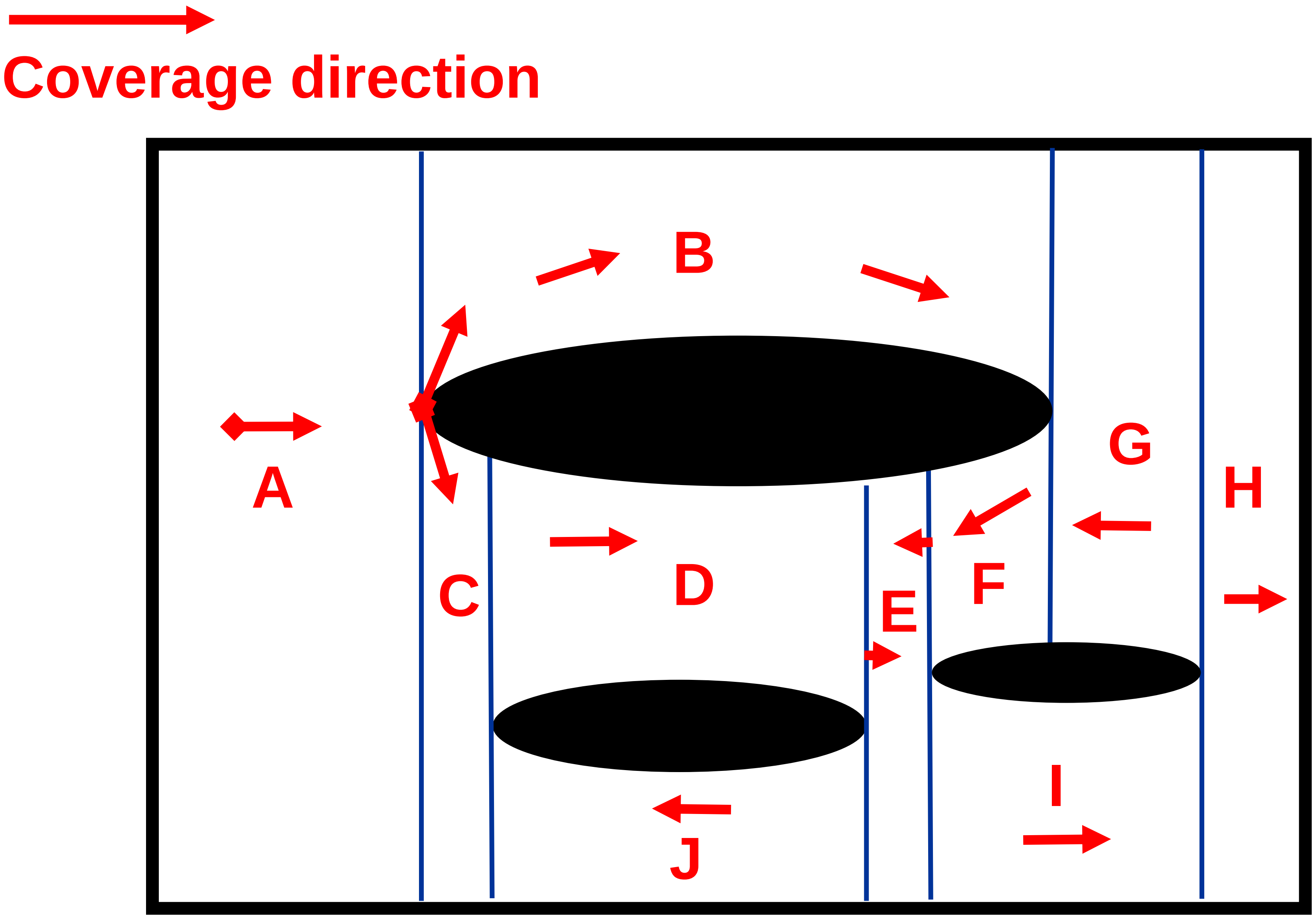


The circles represent the robot position not the sensor footprint.

Team Coverage

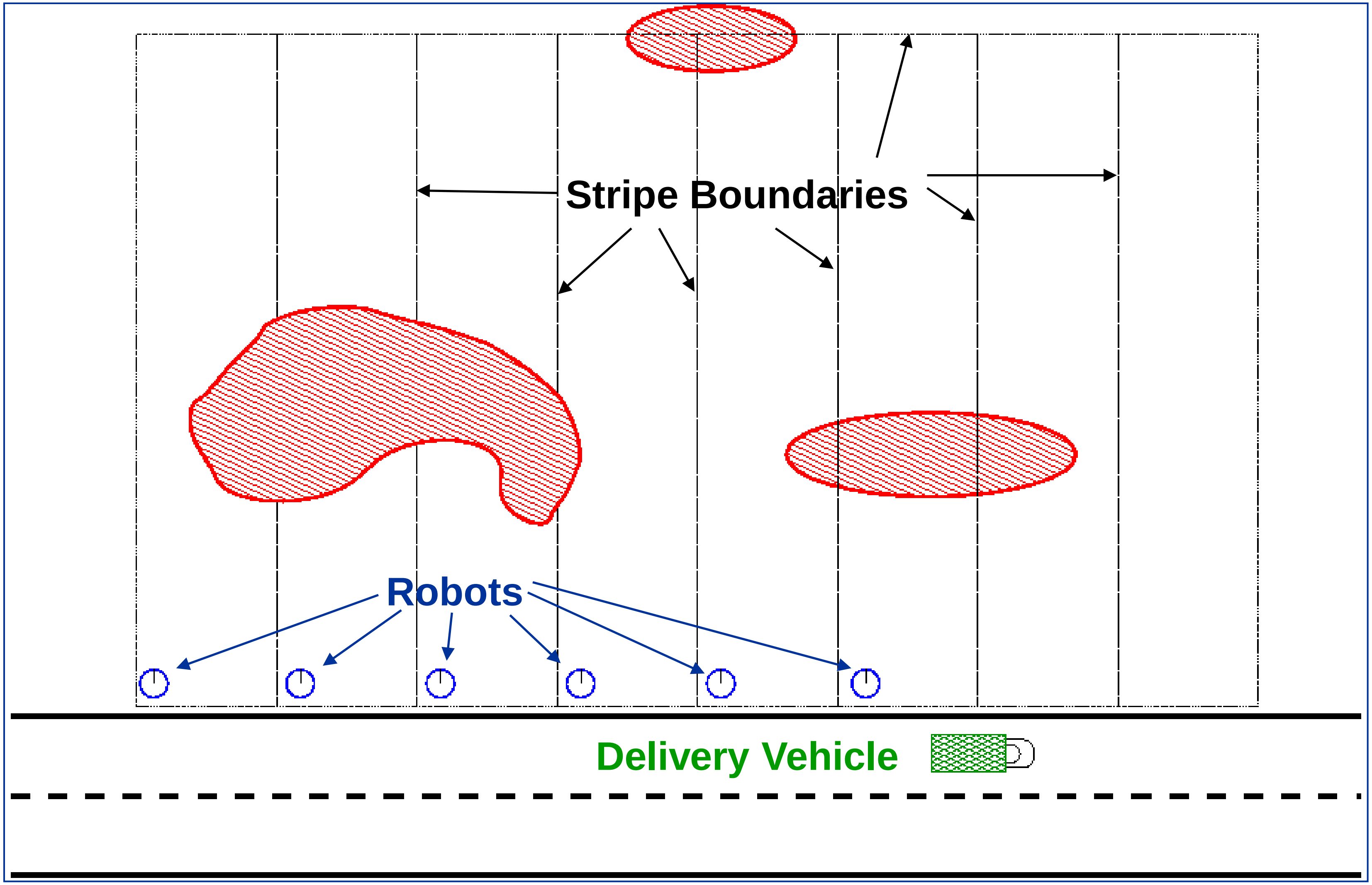
- The team splits only once into two sub-teams in order to encircle an obstacle
- One sub-team moves clockwise around the obstacle, the other sub-team moves counter-clockwise
- If a sub-team encounters a dead-end it backtracks
- Guaranteed re-joining of the two sub-teams

Team Splitting and Rejoining



Coverage Example

Multi-Robot Coverage Paradigm



Multi Robot Complete Coverage
Main Ideas

- Unrestricted Communication / Good Localization
- Environment is divided into as many stripes as robots
- Cooperative Exploration
  - Each robot explores the boundaries of its stripe
  - Robots Auction parts of the non reachable parts of their stripe
- Cooperative Coverage
  - Connectivity of the environment is known
  - Each robot covers the closest cell
  - Robots Auction coverage tasks

Example

- See it on vlc…

Auctions!

- Used to improved performance
- A central coordinator or one team member call/administer the auction
- Robots bid for tasks based on some estimated reward/cost

More Multi-Robot Ideas

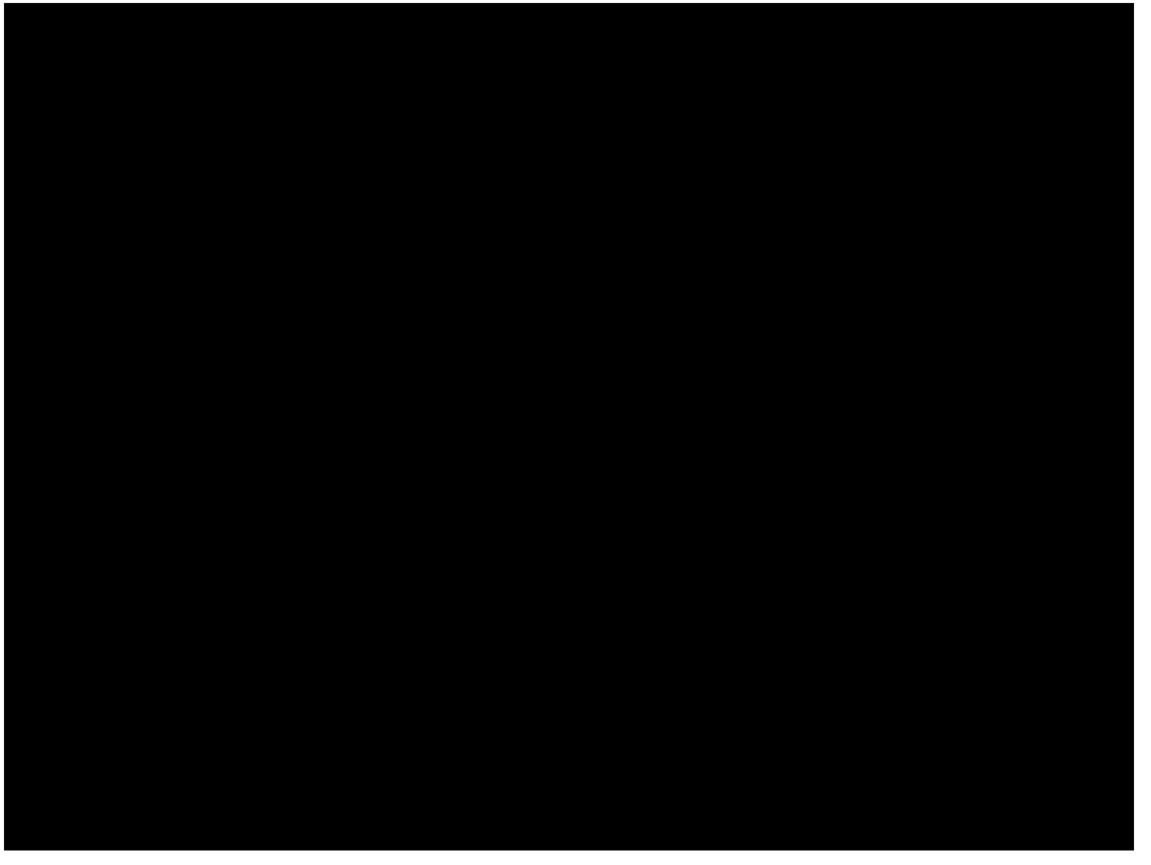
- Marsupial Robots

Also watch: http://www.youtube.com/watch?v=hCGgoPS91Rw

From: http://www.nosc.mil/robots/resources/marsupial/marsupial.html

More Multi-Robot Ideas

- Marsupial Robots



From: http://distrob.cs.umn.edu/demos.php

More Multi-Robot Ideas

- Formations