Navigation and Metric Path Planning

Victoria's crater, on Mars

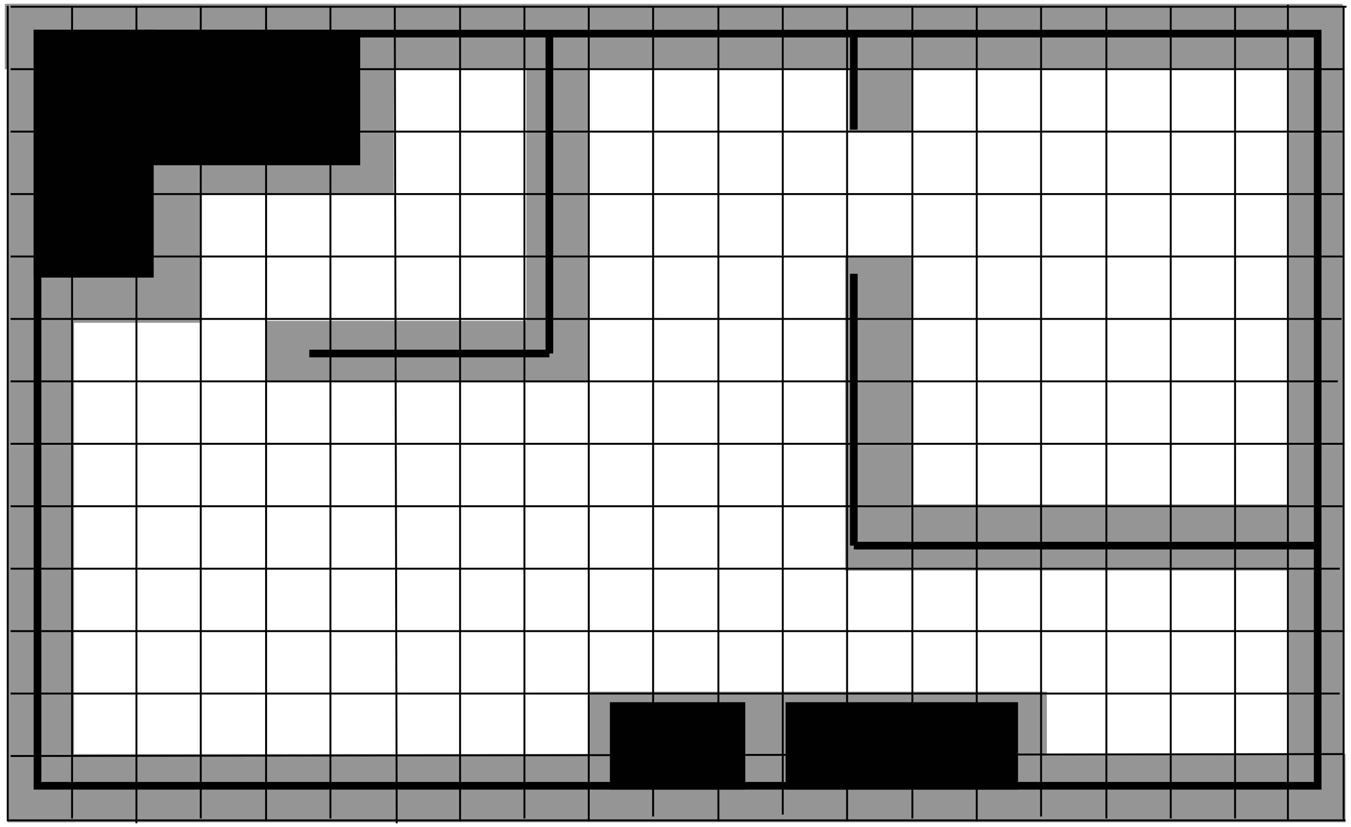
http://thetartan.org/2007/2/19/scitech/mars

JPL robot "Opportunity" being
driven by autonomous path-planning software

Regular Grids / Occupancy Grids

- Superimposes a 2D Cartesian grid on the world space
- If there is any object in the area contained by a grid element, that element is marked as occupied
- Center of each element in grid becomes a node, leading to highly connected graph
- Grids are either considered 4-connected or 8-connected

Example of Regular Grid / Occupancy Grid



Disadvantages of Regular Grids

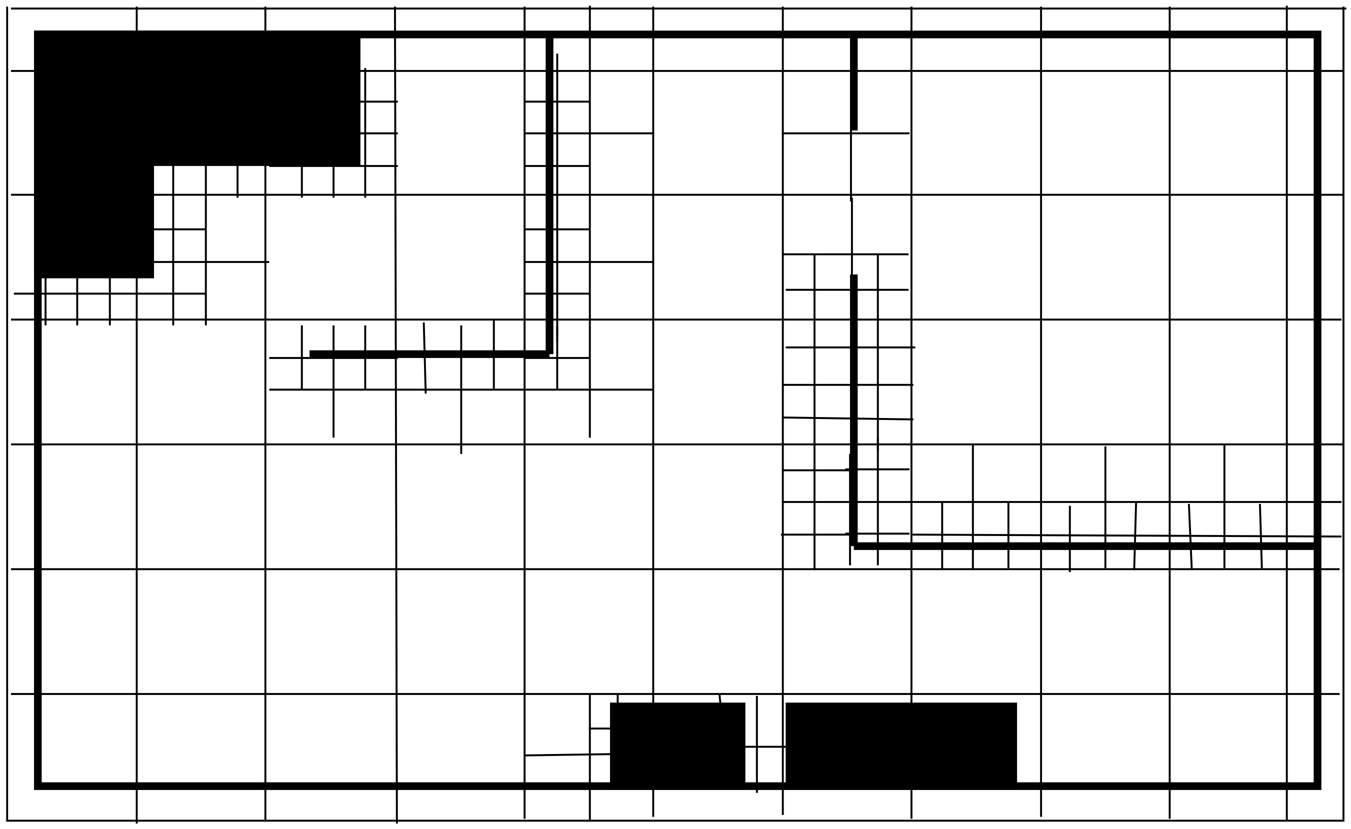
- Digitization bias:
  - If object falls into even small portion of grid element, the whole element is marked as occupied
  - Leads to wasted space
    - Solution: use fine-grained grids (4-6 inches)
    - But, this leads to high storage cost and high # nodes for path planner to consider
- Partial solution to wasted space: Quadtrees

Quadtrees

- Representation starts with large area (e.g., 8x8 inches)
- If object falls into part of grid, but not all of grid, space is subdivided into for smaller grids
- If object doesn’t fit into sub-element, continue recursive subdivision
- 3D version of Quadtree – called an Octree.

Example Quadtree Representation

(Not all cells are subdivided as in an actual quadtree representation (too much work for a drawing by hand!, but this gives basic idea)



Graph Based Planners

- Finding path between initial node and goal node can be done using graph search algorithms
- Graph search algorithms: found in networks, routing problems, etc.
- However, many graph search algorithms require visiting each node in graph to determine shortest path
  - Computationally tractable for sparsely connected graph (e.g., Voronoi diagram)
  - Computationally expensive for highly connected graph (e.g., regular grid)
- Therefore, interest is in "branch and bound" search
  - Prunes off paths that aren't optimal
- Classic approach: A* search algorithm
  - Frequently used for holonomic robots

“A” Search Algorithm

- “A” search:
  - Produces optimal path
  - Starts at initial node and works way to goal node
  - Generates optimal path incrementally
  - Each update: considers nodes that could be added to the path, and selects best one
  - Evaluation function:

    $f(n) = g(n) + h(n)$

    where:

    $f(n)$ measures how good the move to node n is

    $g(n)$ measures cost of getting to node n from initial node

    $h(n)$ is the cheapest cost of getting from n to goal
- Problem: assumes you know $h(n)$ for all nodes, which means you have to visit all nodes to recurse in order to find $h(n)$

A* Search Algorithm

- A* (read “A star”) search:
  - Reduces number of paths to be explored
  - No need to explore a path if it cannot be a good path
  - Estimates $h(n)$, even if no actual path available
  - Use this estimate to prune out paths that cannot be good
  - A* Evaluation function:

    $f^*(n) = g^*(n) + h^*(n)$

    where:

    * means these are estimates
  - In path planning, $g^*(n)$ is equivalent to $g(n)$

- How to estimate $h(n)$?

Estimating *h*(*n*)

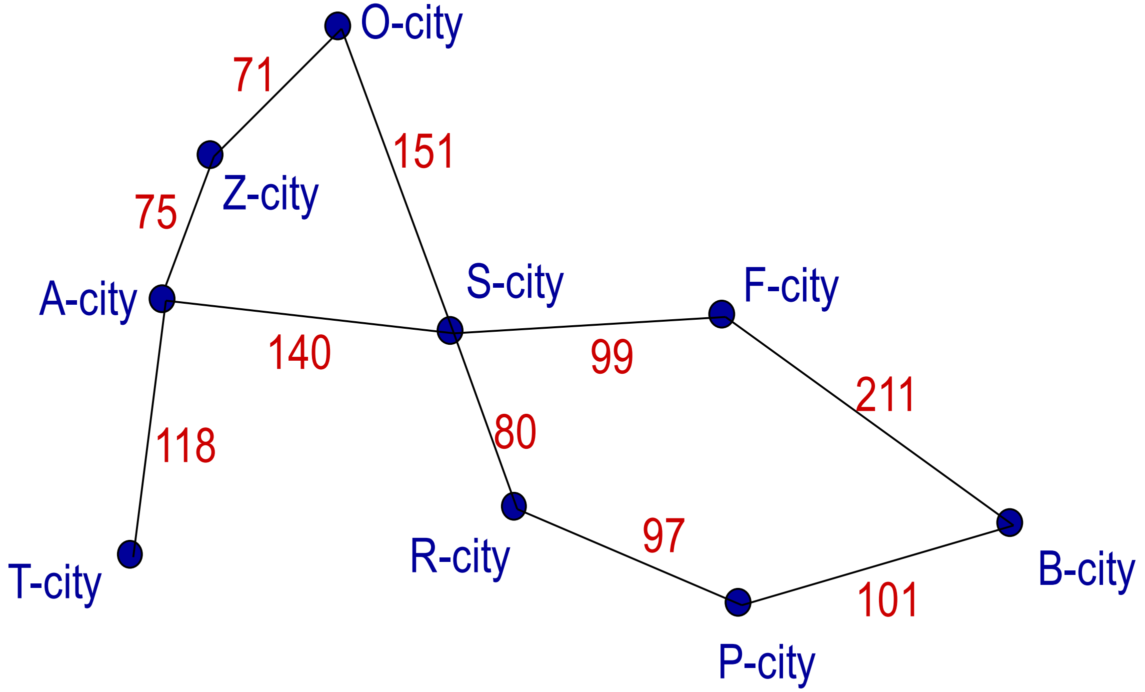
- Must ensure that *h**(*n*) is never greater than *h*(*n*)
- Admissibility condition:
  - Must always underestimate remaining cost to reach goal
- Easy way to estimate:
  - Use Euclidian (straight line) distance
  - Straight line will always be shortest path
  - Actual path may be longer, but admissibility condition still holds

Example of A*

Compute optimal path from A-city to B-city

Straight-line distance to B-city from:

A-city:	366
B-city:	0
F-city:	176
O-city:	380
P-city:	98
R-city:	193
S-city:	253
T-city:	329
Z-city:	374



Method for Example

- Expand each node from A-city, computing $f^*(n) = g^*(n) + h^*(n)$
- (Example worked on board)

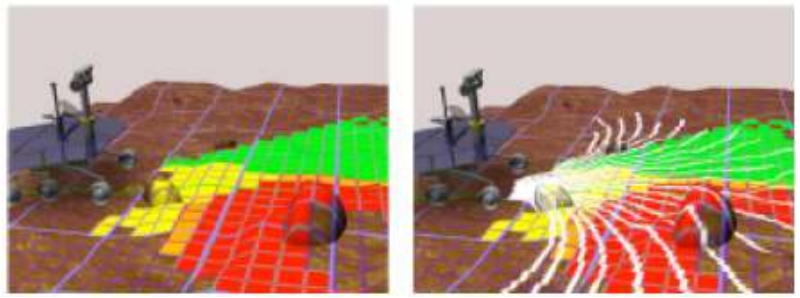
Pros and Cons of A* Search/Path Planner

- Advantage:
  - Can be used with any Cspace representation that can be transformed into a graph
- Limitation:
  - Hard to use for path planning when there are factors to consider other than distance (e.g., rocky terrain, sand, etc.)

Extension to A* = D*

- D*: initially plans path to goal just like A*, but plans a path from every position to the goal in advance
  - I.e., rather than "single source shortest path" (Dijkstra's algorithm),
    - Solve "all pairs shortest path" (e.g., Floyd-Warshall algorithm)

- In D*, the estimated distance, h*, is based on traversability



Calculate traversability using stereo cameras; can also manually mark maps

- Then, D* continuously replans, by updating map with newly sensed information
  - Approach: "repair" pre-planned paths based on new information

D* Applied Recently to Mars Rover "Opportunity"

Victoria crater, on Mars

Rover "Opportunity"

Opportunity
Rover tracks
"Cape Verde"
"Duck Bay"
"Cabo Frio"

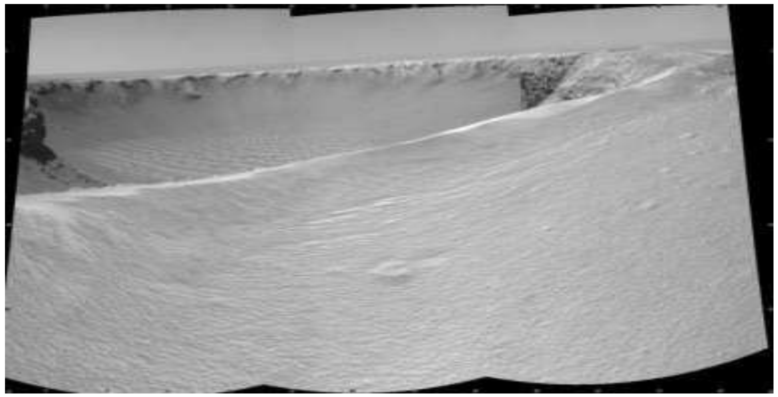
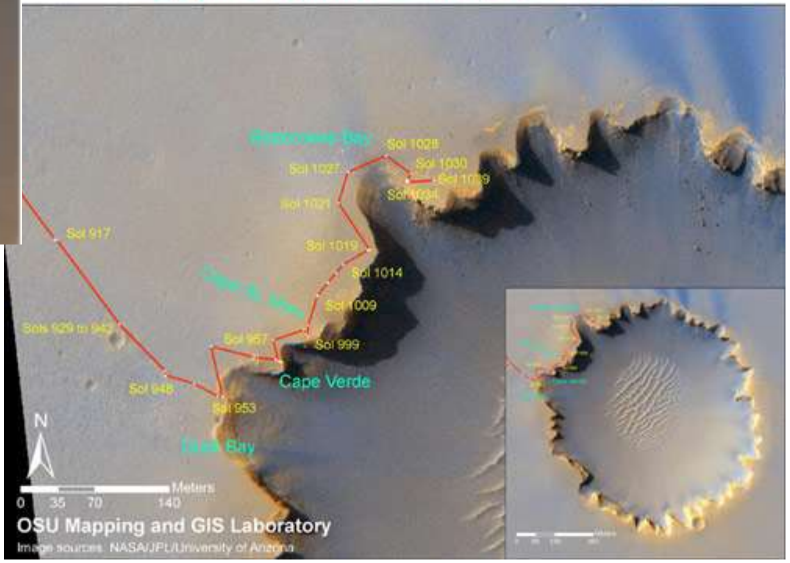


Image of Victoria crater, taken by rover "Opportunity"

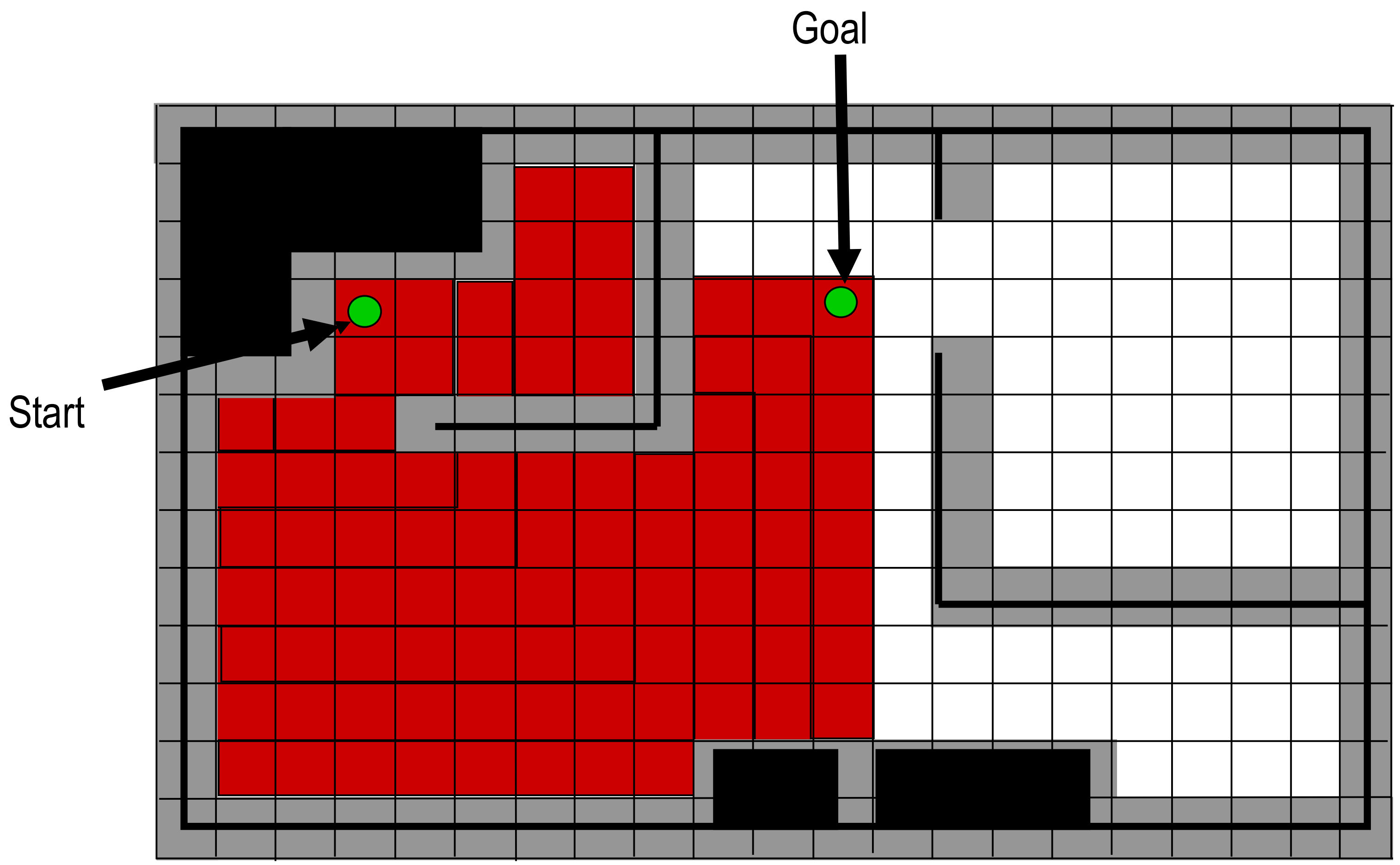
Opportunity Traverse Map (Sol 1039)



Wavefront-Based Path Planners

- Well-suited for grid representations
- General idea: consider Cspace to be conductive material with heat radiating out from initial node to goal node
- If there is a path, heat will eventually reach goal node
- Nice side effect: optimal path from all grid elements to the goal can be computed
- Result: map that looks like a potential field

Example of Wavefront Planning



Algorithmic approach for Wavefront Planning

<u>Part I: Propagate wave from goal to start</u>

- Start with binary grid; 0's represent free space, 1's represent obstacles
- Label goal cell with "2"
- Label all 0-valued grid cells adjacent to the "2" cell with "3"
- Label all 0-valued grid cells adjacent to the "3" cells with "4"
- Continue until wave front reaches the start cell.

<u>Part II: Extract path using gradient descent</u>

- Given label of start cell as "x", find neighboring grid cell labeled "x-1"; mark this cell as a waypoint
- Then, find neighboring grid cell labeled "x-2"; mark this cell as a waypoint
- Continue, until reach cell with value "2" (this is the goal cell)

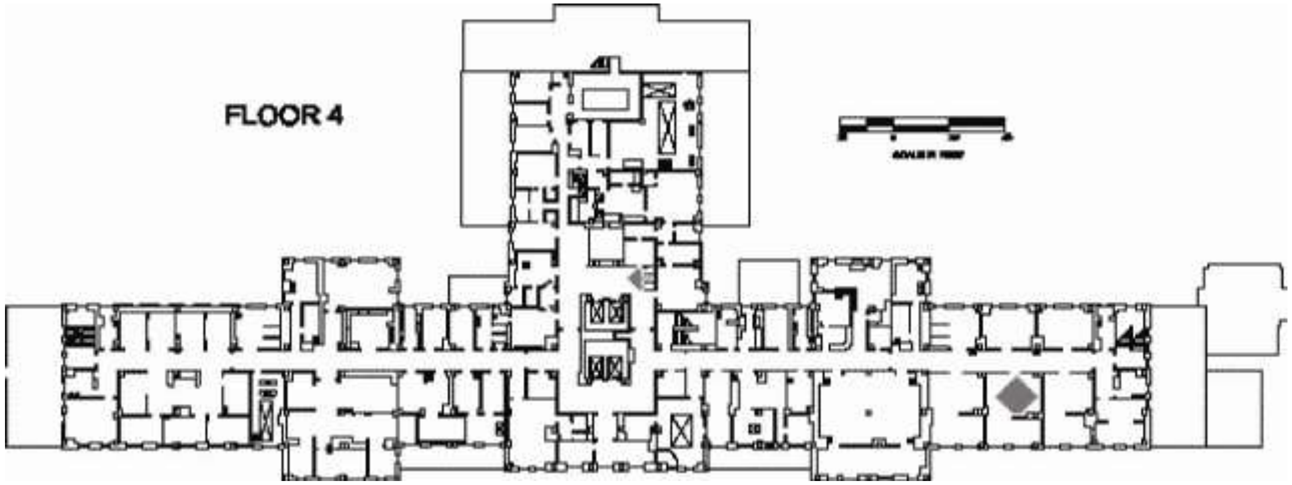
<u>Part III: Smooth path</u>

- Iteratively eliminate waypoint i if path from waypoint i-1 to i+1 does not cross through obstacle
- Repeat until no other waypoints can be eliminated
- Return waypoints as path for robot to follow

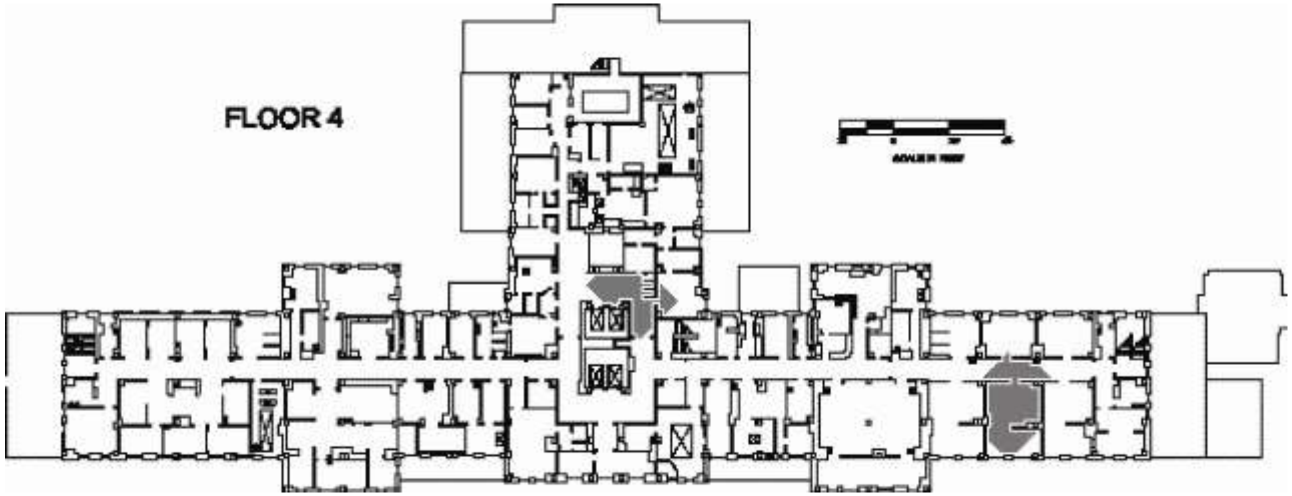
Wavefront Propagation Can Handle Different Terrains

- Obstacle: zero conductivity
- Open space: infinite conductivity
- Undesirable terrains (e.g., rocky areas): low conductivity, having effect of a high-cost path
- Also: To save processing time, can use *dual* wavefront propagation, where you propagate from both start and goal locations

Example Using Dual Wavefront Propagation

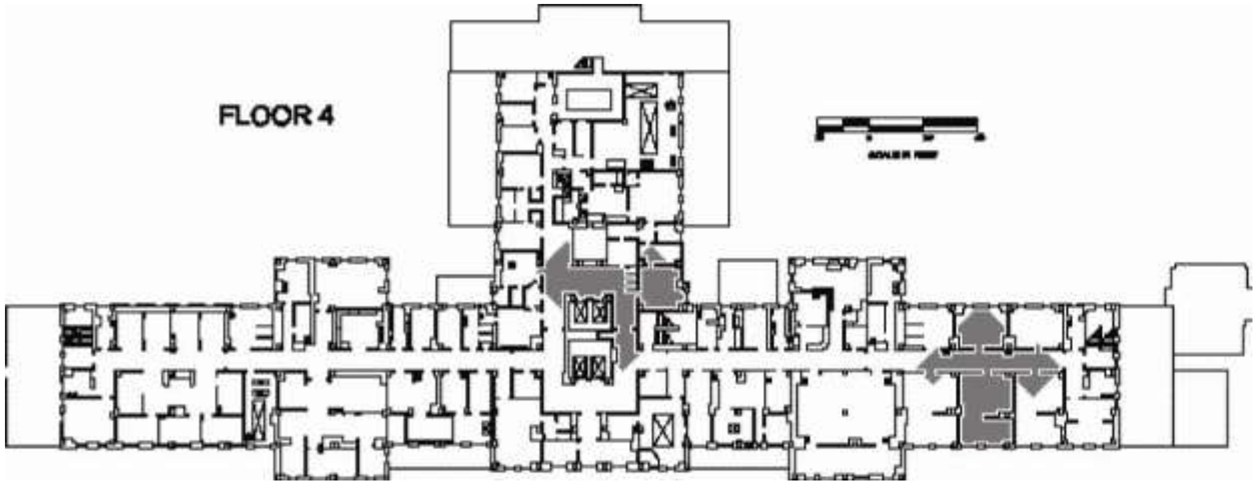


10 Iterations

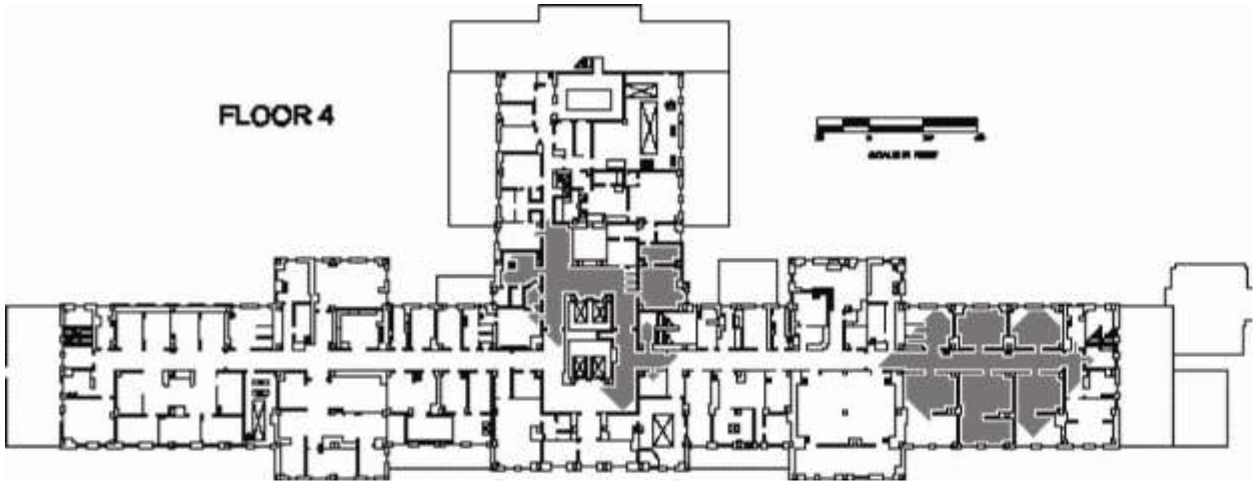


30 Iterations

Dual Wavefront Propagation in Progress

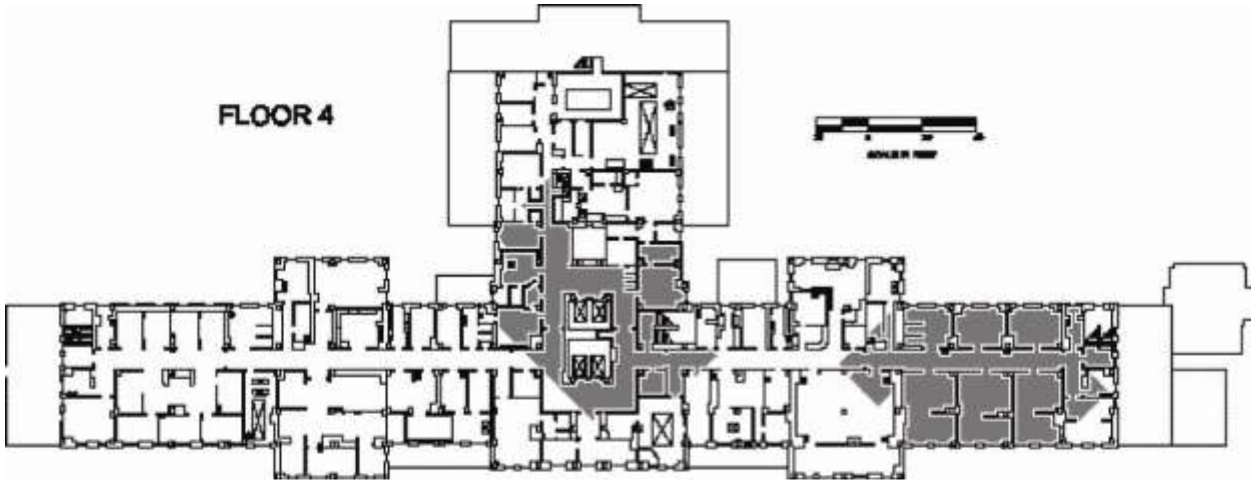


50 Iterations

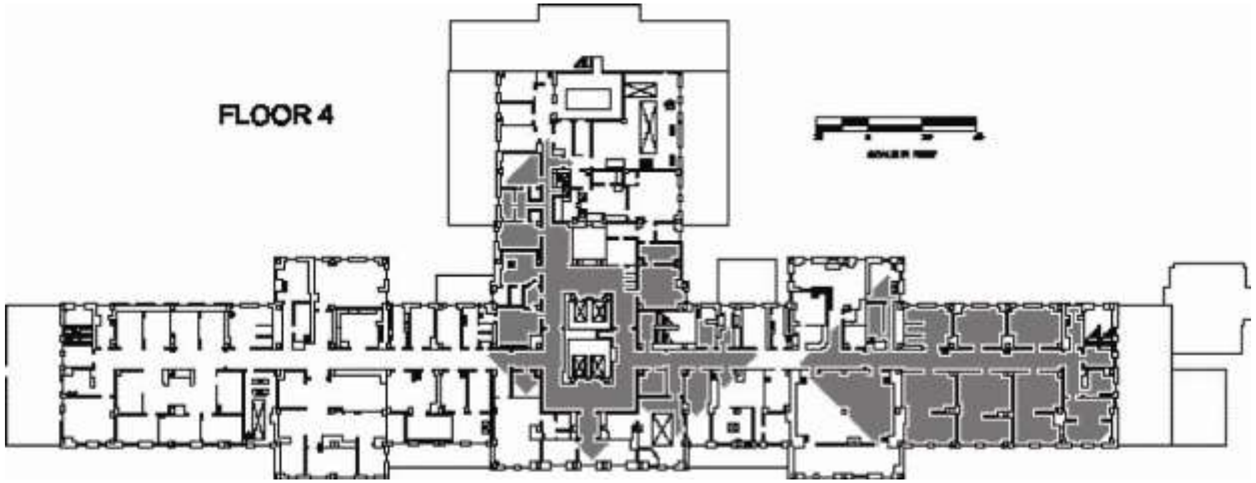


70 Iterations

Dual Wavefront Propagation in Progress (con't.)

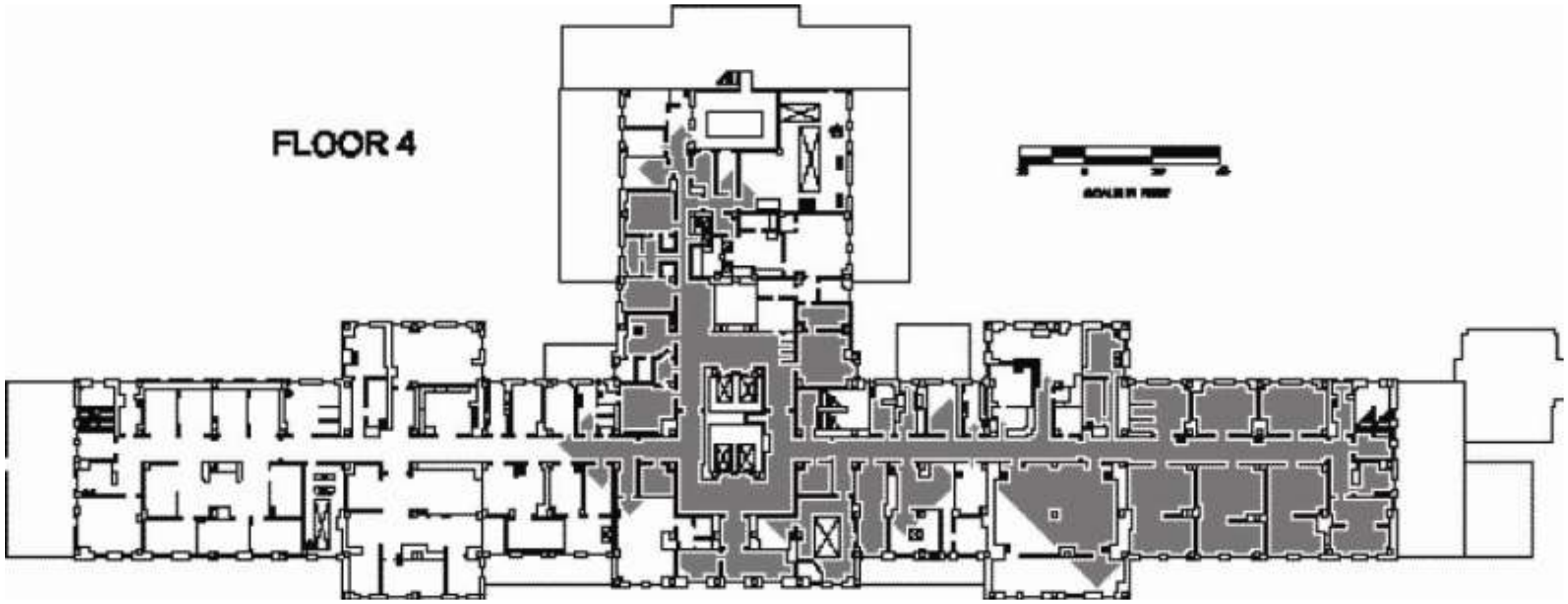


90 Iterations



110 Iterations

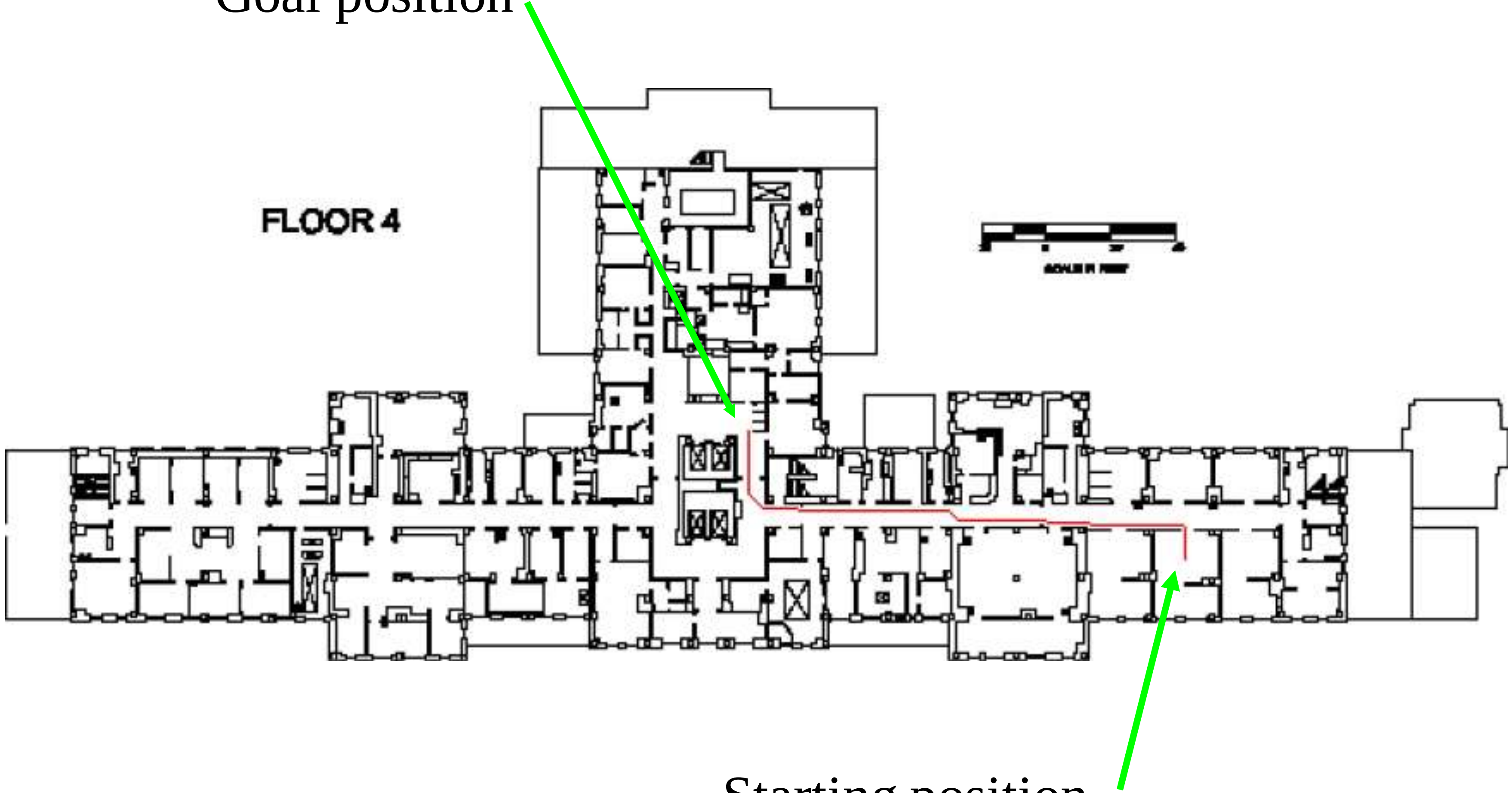
Dual Wavefront Propagation in Progress (con't.)



Propagation complete.

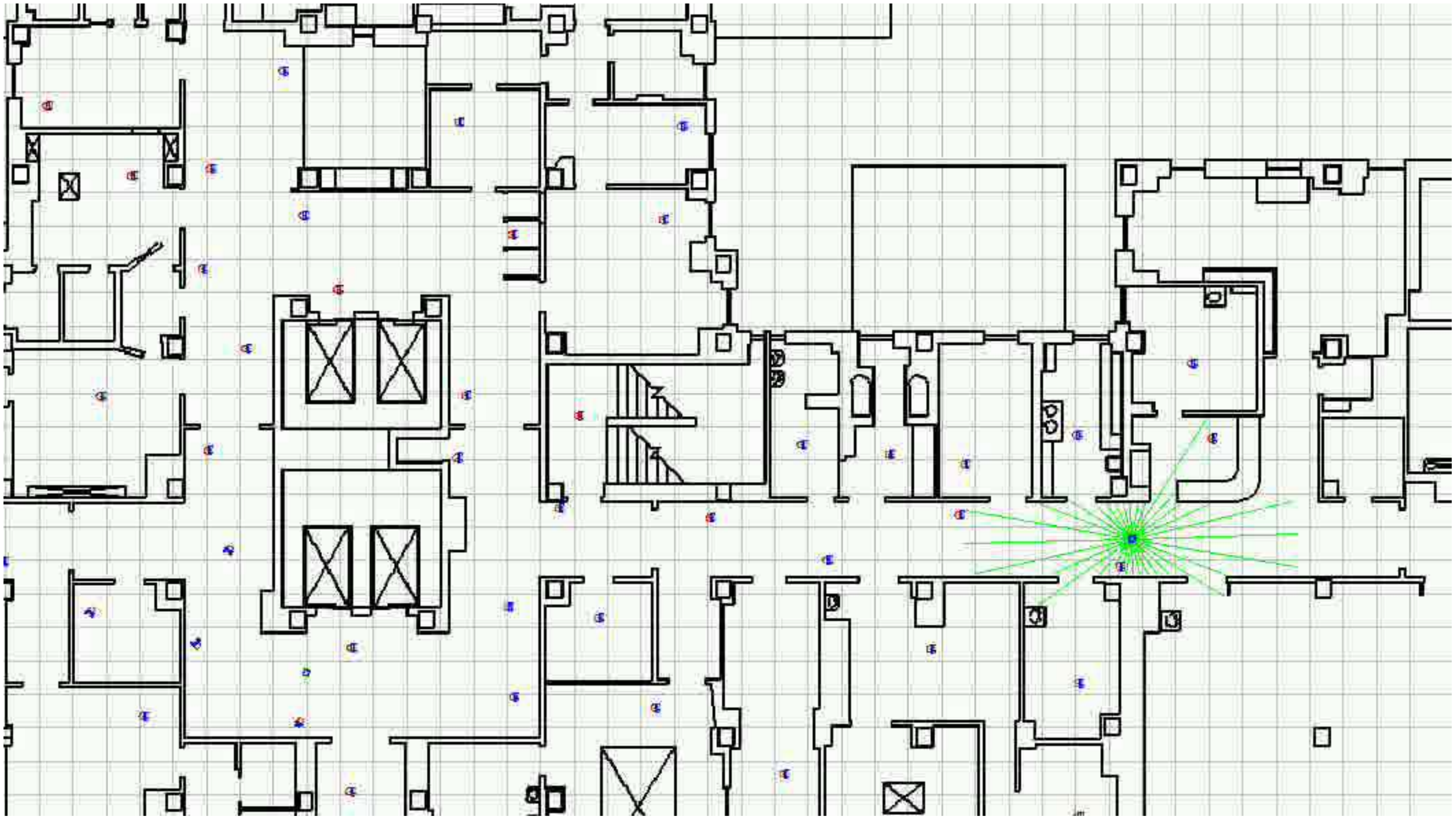
Extracted Path

Goal position



Starting position

Movie of robot using wavefront planner



Summary of Metric Path Planning

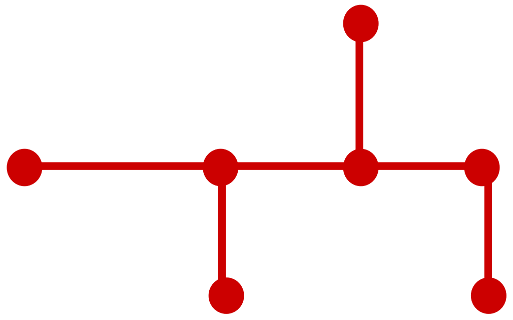
- Converts world space to a configuration space
- Use obstacle growing to enable representation of robot as a point
- Cspace representations exploit interesting geometric properties of the environment
- Representations can be converted to graphs
- A* works well with Voronoi diagrams, since they produce sparse graphs
- Wavefront planners work well with regular grids
- Metric path planning tends to be computationally expensive
- Limitation of popular path planners: assume holonomic robots

Topological Navigation and Path Planning

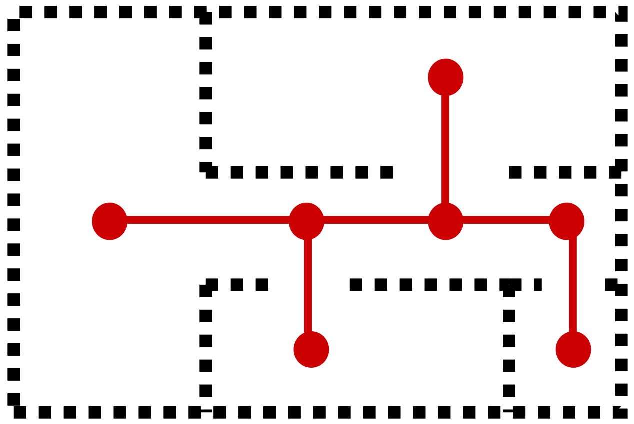
- Based upon points of interest
  - E.g., landmarks
- Navigation is relational between points of interest
  - E.g., “Go past the corner and enter the second doorway on the left”
- Precise metric information not used
- Approaches are usually based upon graph representations

Recall: Difference between Topological and Metric

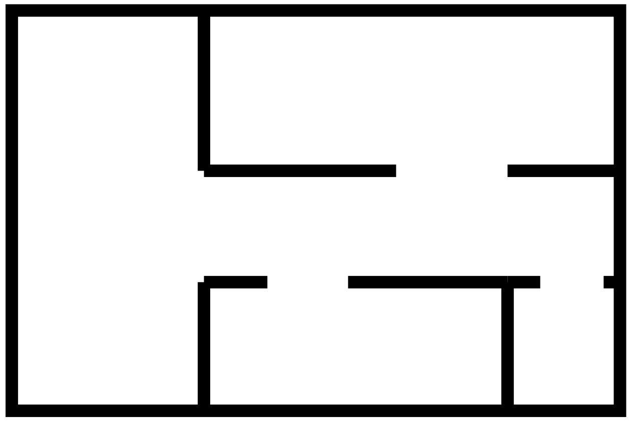
- Qualitative (topological, route):



derived from:



- Quantitative (metric or layout):



Landmarks

- Landmark:
  - One or more perceptually distinctive features of interest on on object or locale of interest
  - Examples: corner, doorway, tree, sign, marker
  - Can be “artificial” or “natural”
    - Artificial → placed for the purpose of aiding navigation
    - Natural → existing features not expressly designed for aiding navigation

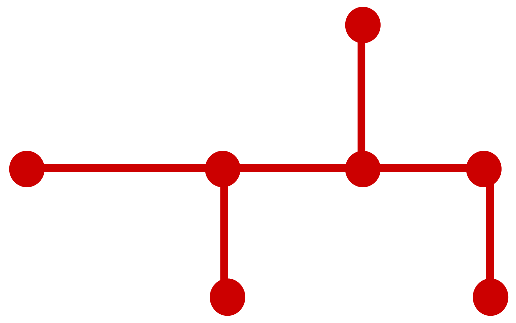
- Gateways:
  - Special case of landmark, where robot has opportunity to change its overall direction of navigation
  - Examples: intersection of hallways

Important Criteria for Landmarks

1. Must be readily recognizable
2. Must support the task dependent activity
3. Must be perceivable from many different viewpoints

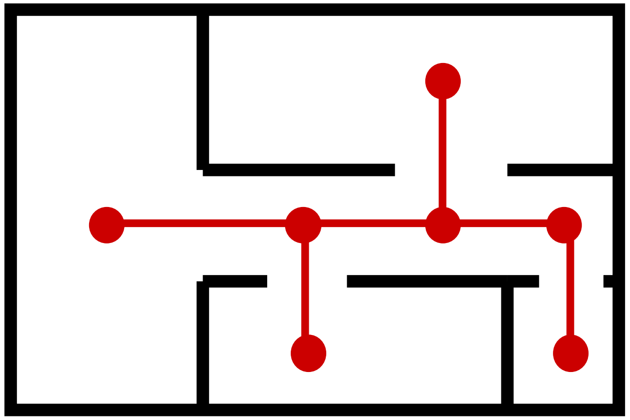
Relational Methods

- Represent world as graph or network of nodes and edges
  - Nodes: represent gateways, landmarks, or goals
  - Edges: represent a navigable path between two nodes; can also have additional information attached (e.g., direction, terrain type, behaviors needed to navigate the path)

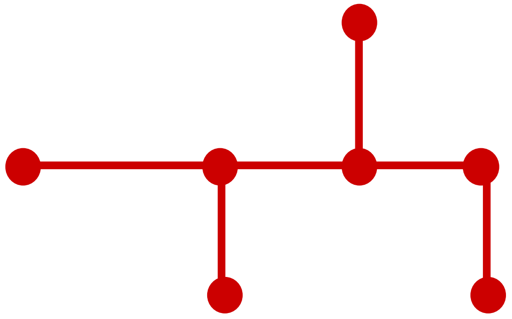


Multi-Level Spatial Hierarchy (Byun & Kuipers)

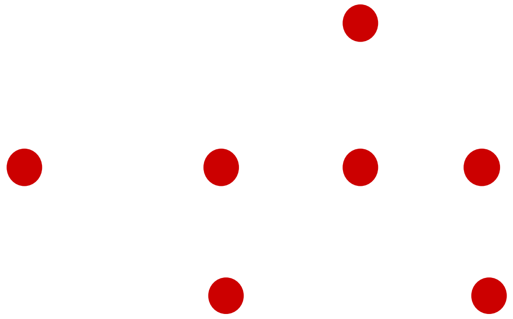
- Metric: distances, directions, shapes in coordinate system



- Topological: connectivity



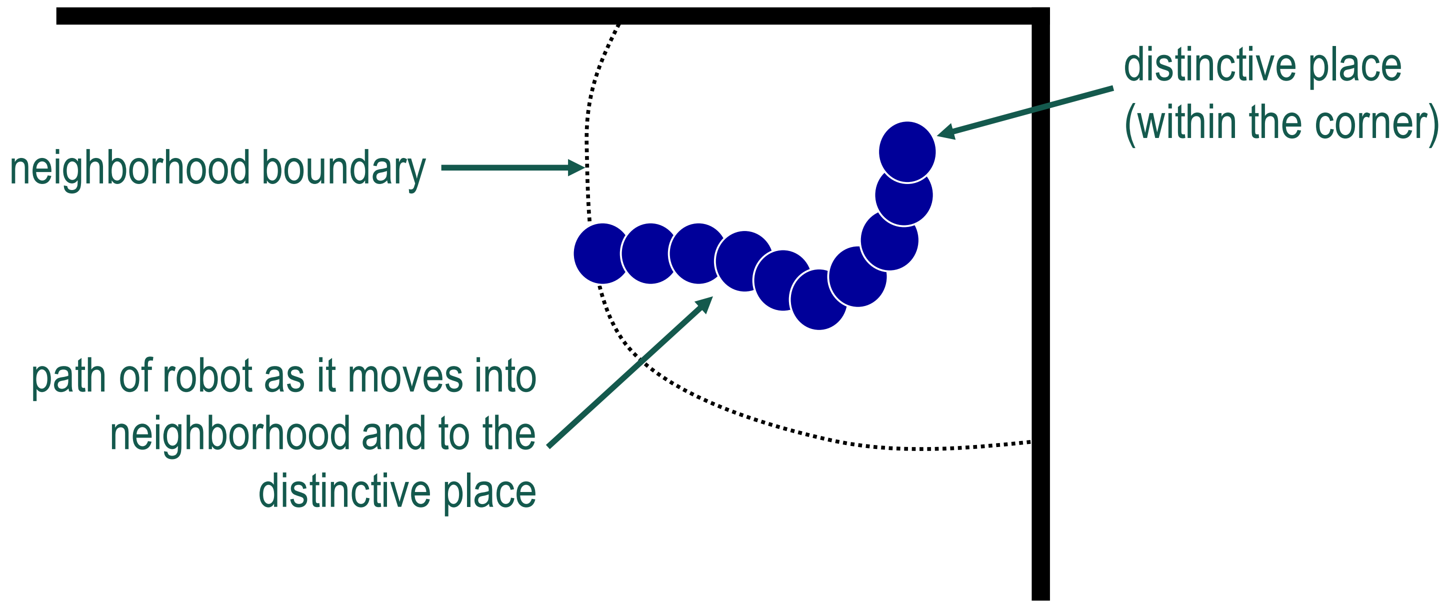
- Landmark definitions, procedural knowledge for traveling



Distinctive Places

- Distinctive place: landmark that robot can detect from nearby region called "neighborhood"
- Once robot in the neighborhood, it uses sensors to position itself relative to the landmark
- Edge in the relational graph: local control strategy (lcs)
  - Procedure for getting from current node to next node
- When landmark sensed, "hill-climbing" used to desired relative position
- Maximum value = distinctive place

Example of Distinctive Place

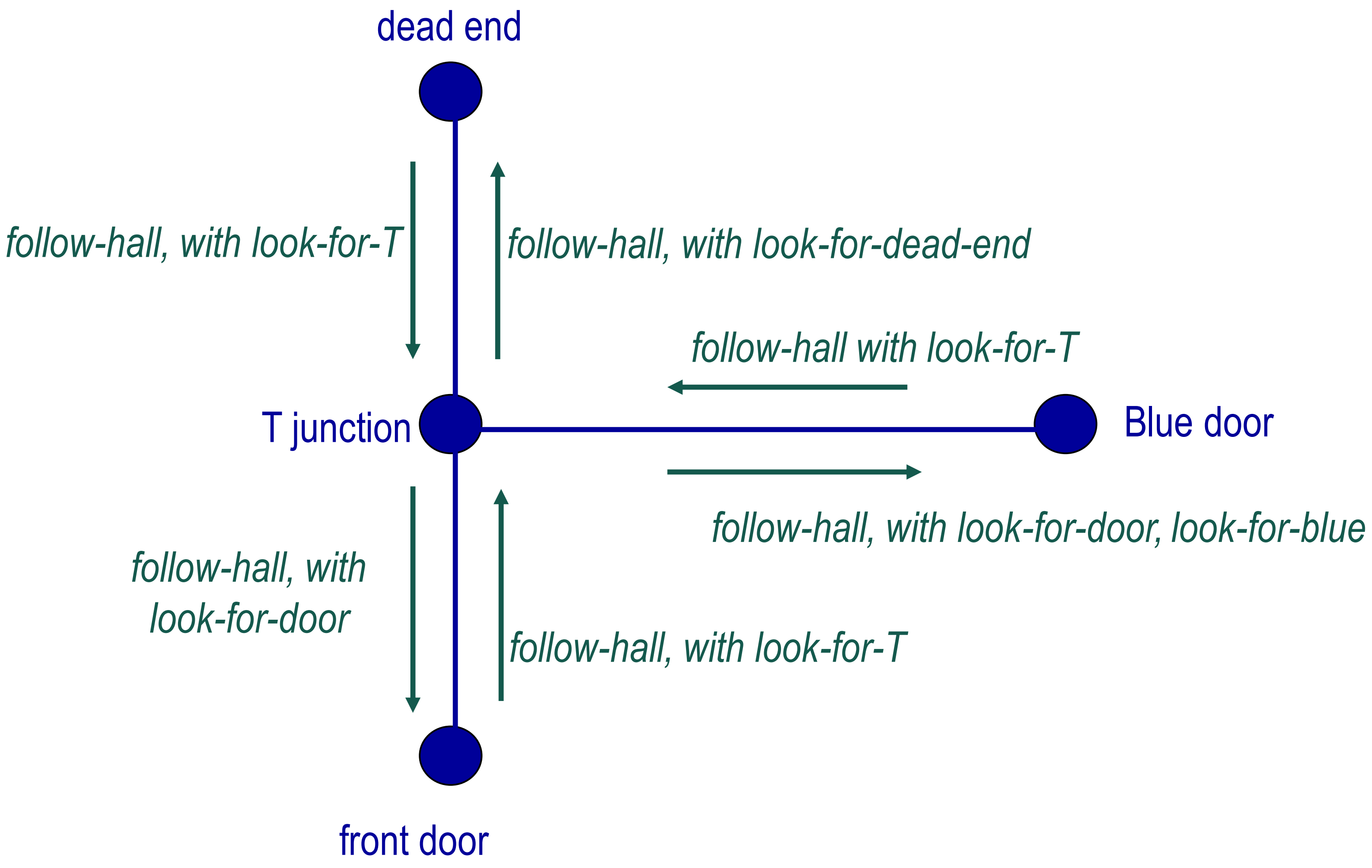


Robot moves to distinctive place using sensor-based local control strategy and hill-climbing

Example of Local Control Strategies

Basic behavior: *follow-hall*

Releasers: *look-for-T, look-for-dead-end, look-for-door, look-for-blue*


dead end
follow-hall, with look-for-T
follow-hall, with look-for-dead-end
follow-hall with look-for-T
T junction
Blue door
follow-hall, with look-for-door, look-for-blue
follow-hall, with look-for-door
follow-hall, with look-for-T
front door

Distinctive Places: Advantages and Disadvantages

- Advantages:
  - Eliminates concern over navigational errors at each node
  - Robot can build up metric information over multiple trips, since error will average out
  - Supports discovery of new landmarks

- Disadvantages:
  - Difficult to find good distinctive places
    - Either too numerous, and thus not locally unique
    - Or, too few, and thus hard to find
  - Difficult to define and learn local control strategies