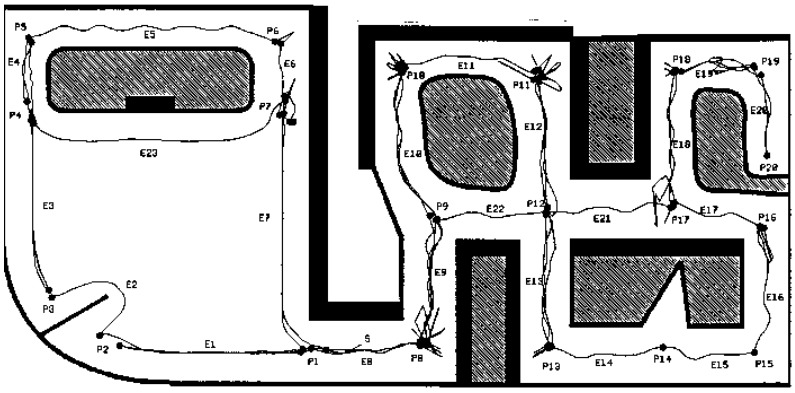
Lecture 19:
Topological Mapping

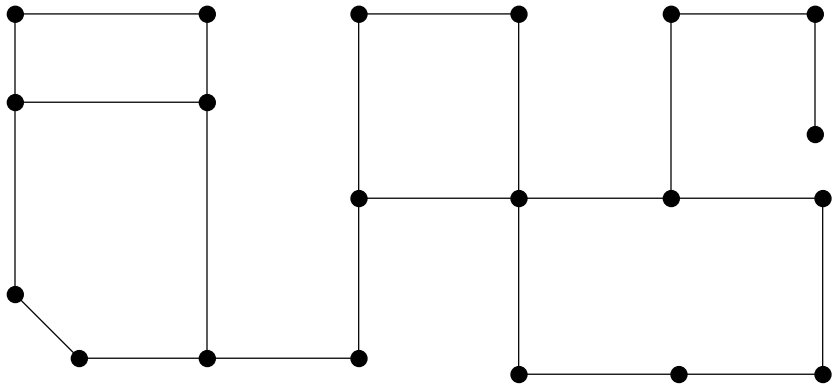
CS 344R/393R: Robotics

Benjamin Kuipers

Exploration Defines Important Places and Paths



Abstract the Exploration Pattern to the Topological Map



The Topological Map

- The *topological map* is the set of places and edges linking them.
- A *place* is a decision point among edges.
  - It has a *local topology*: radial order among edges.
  - It has a *local geometry*: directions of edges.
- An *edge* links two places.
  - An edge has a control law for travel along it.

Scale of Space

- **Small-scale space** is within the agent's perceptual surround.
  - "visual space" or "perceptual space"
- **Large-scale space** has structure that must be integrated from the agent's observations gathered over time and travel.
  - the "cognitive map"

Two Approaches to Distinctive States and Places

- Hill-climb to a distinctive state
  - Makes very weak assumptions about sensors
  - Voronoi graph: points equidistant from nearby obstacles
- **Localize in place neighborhood**
  - Requires local metrical map of neighborhood
  - Use Voronoi graph to define local topology

What is a Place?

- In **small-scale space**:
  - A place is a *region*.
  - It's a neighborhood where the agent can reliably localize itself completely.
  - It's bounded by *gateways*, which connect to path segments for travel to other places.
- In **large-scale space**:
  - A place is a *decision point*.
  - It's a graph node connected to other places, representing a 0-D location.

Topological Mapping Overview

- **Build local perceptual maps** of place neighborhoods, each a small-scale space.
- **Build local topology descriptions** of the complete qualitative structure of each place neighborhood.
- **Build the global topological map** abductively, using:
  - completeness of the local topology description,
  - pose in local topology to serve as a "view".

Local Place Neighborhood Map

- For each place neighborhood, build a small local metrical map, with its own frame of reference.
  - Use it for "virtual range sensing" when specular reflection makes sonar sensors unreliable.
- Put the origin at a central point, and store directions of outgoing edges.
  - Store the local map as an attribute of the place.

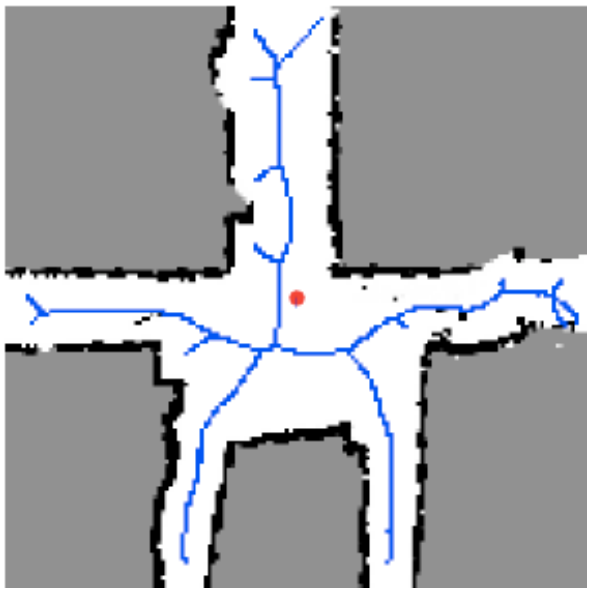
A Scrolling Metrical Map

- During travel, maintain a limited-range metrical map of immediate surroundings.
  - Keep robot pose (x,y) in the center cell.
  - Robot's orientation θ can vary in the map.
  - Robot pose is high resolution, not map cell.
- Scroll the *map* as the robot moves.
  - Shift in (x,y) only, not in orientation.
  - Shift only by integral numbers of cells, to prevent information loss.
- Cells that fall off the edge are lost.

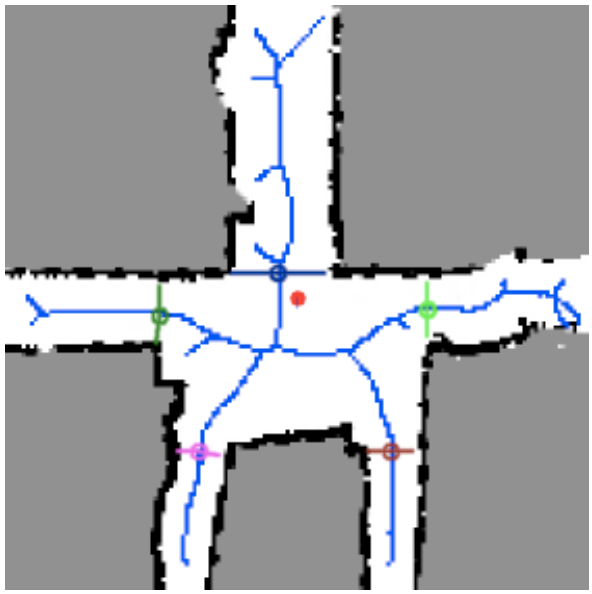
Gateways

- A gateway is a transition between a *travel action* and a *place neighborhood*
  - i.e., between a trajectory-following control law and a local perceptual map.
  - Transitions can be *inbound* or *outbound*.
  - Detected from local properties of the environment and the conditions on the control law.

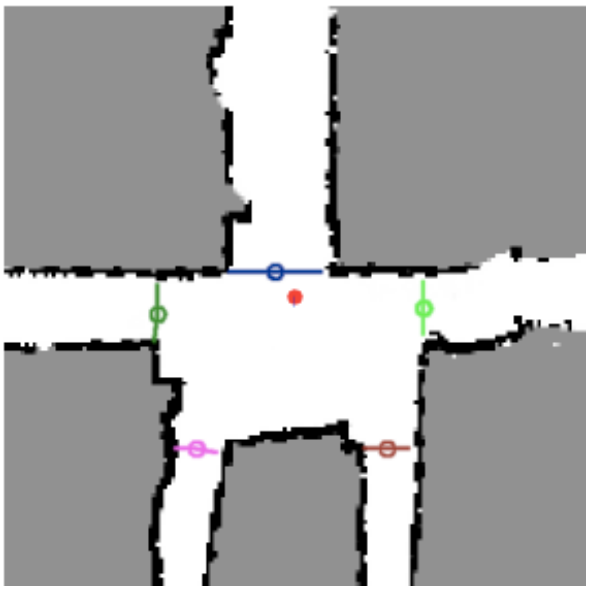
Detect and Describe a Place



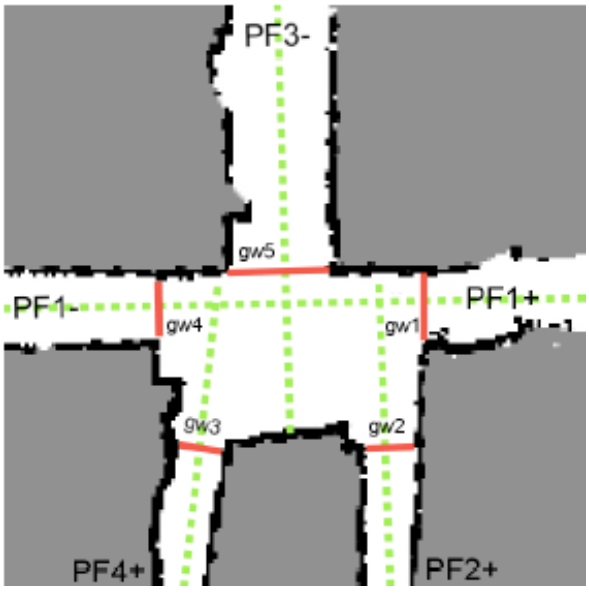
Identify Constrictions



Define Gateways



Define Local Path Fragments



Local Topology Description

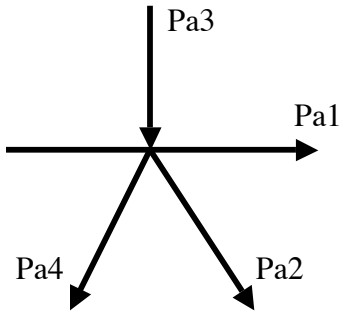
- The *small-scale star* is a circular order of path fragments, gateways, and control laws.

PF1+	(gw1,out) & (gw4,in)	Midline
PF2+	(gw2,out)	Midline
PF3+	(gw5,in)	DeadEnd
PF4+	(gw3,out)	Midline
PF1-	(gw4,out) & (gw1,in)	Midline
PF4-	(gw3,in)	DeadEnd
PF3-	(gw5,out)	Midline
PF2-	(gw2,in)	DeadEnd

Local Topology Description

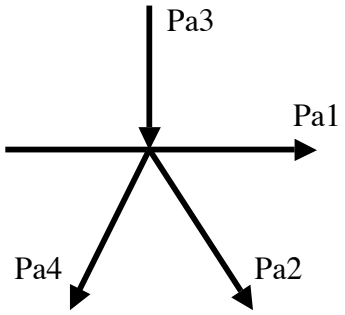
- The *large-scale star* describes the place with distinctive states and directed paths.

ds1	Pa1, +	
ds2	Pa2, +	
ds3	Pa3, +	Endpoint
ds4	Pa4, +	
ds5	Pa1, –	
ds6	Pa2, –	Endpoint
ds7	Pa3, –	
ds8	Pa4, –	Endpoint

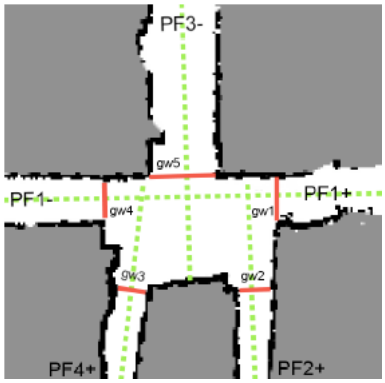


Turn Actions

- A Turn action may follow a trajectory through the local place neighborhood.

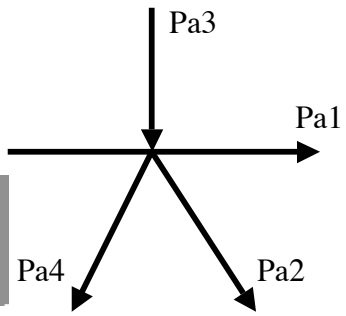


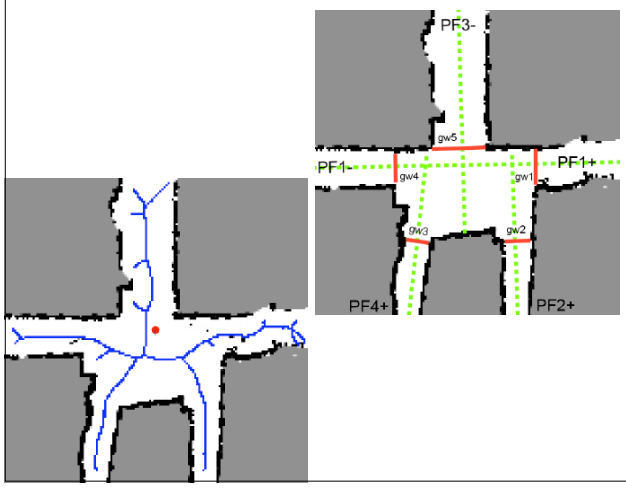
in large-scale space



in small-scale space

Topology from Local Metrical Maps





Places and Gateways

- The agent can localize reliably anywhere in a place neighborhood.
  - Gateways act as distinctive states
  - *state* = (*place*, *gateway*, *orientation*)
- Actions move the agent deterministically, from one state to another,.
  - **Travel**: from *outbound* gateway at one place neighborhood to *inbound* gateway at another
  - **Turn**: from *inbound* to *outbound* gateway at a place neighborhood
- Every $\langle q, \mathit{Turn}, q' \rangle$ at a place is known.

Does a place abstraction always exist?

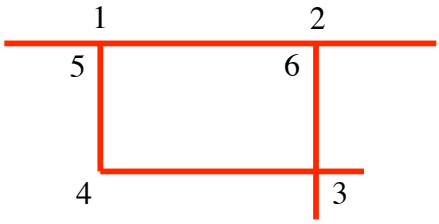
- Not in truly pathological environments
  - open ocean

  or with pathological sensors
  - video snow
- **Conjecture: Yes**, with sufficiently rich sensors in a sufficiently rich environment.
  - office environments
  - campus/urban indoor/outdoor environments

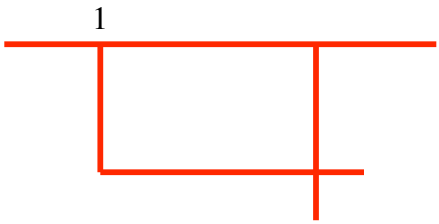
Build the Global Topological Map

- Define a tree of *all possible* topological maps consistent with exploration experience.
  - They are the leaves of this tree.
- For each new action+observation
  - If the map predicts the observation, OK.
  - If it contradicts the observation, prune it.
  - Otherwise, branch on maps with new edges:
    - All possible loop-closing hypotheses
    - One hypothesis of a brand-new place
  - Identify the current best map.

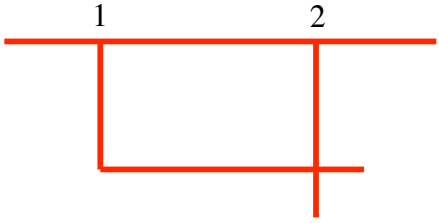
Building the Tree of Maps

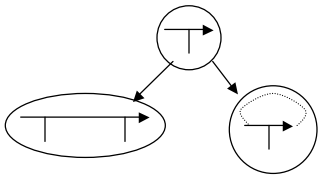


Tree of Maps (1)

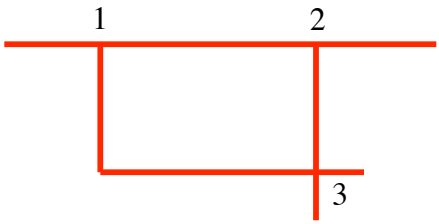


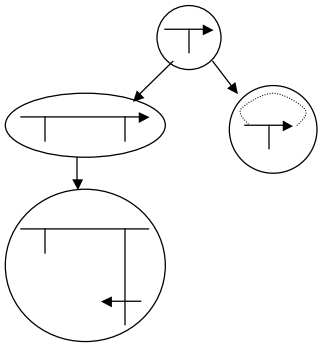
Tree of Maps (2)



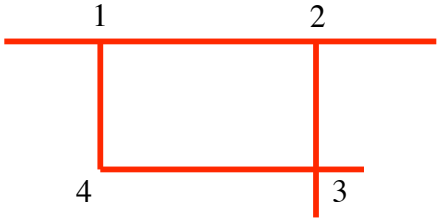


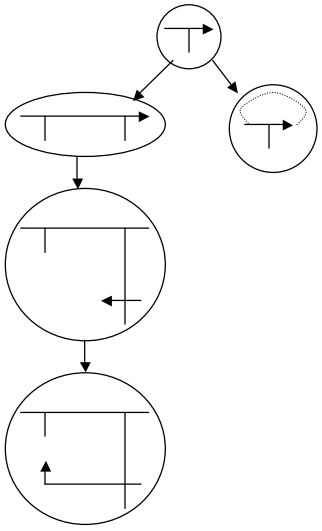
Tree of Maps (3)



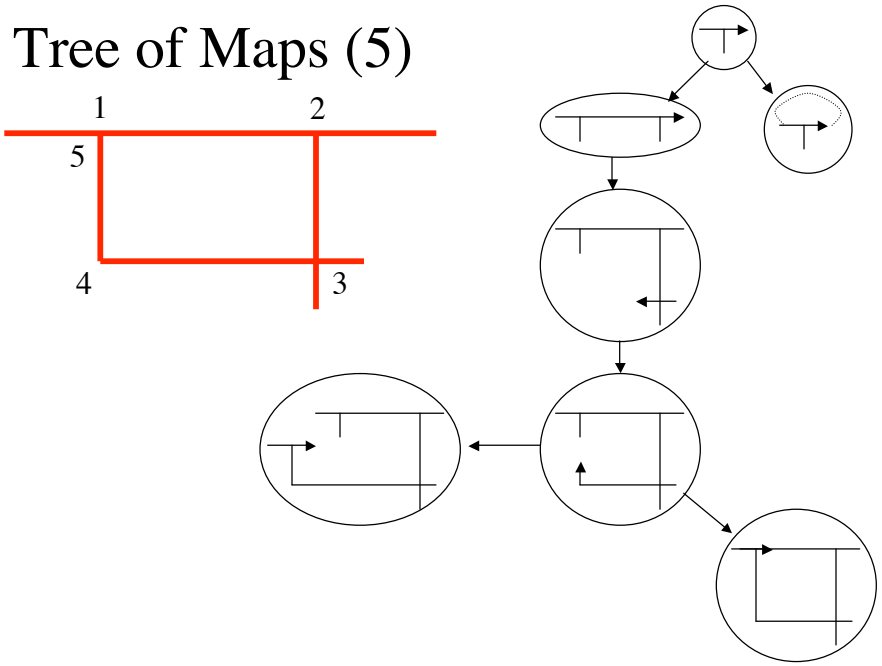


Tree of Maps (4)

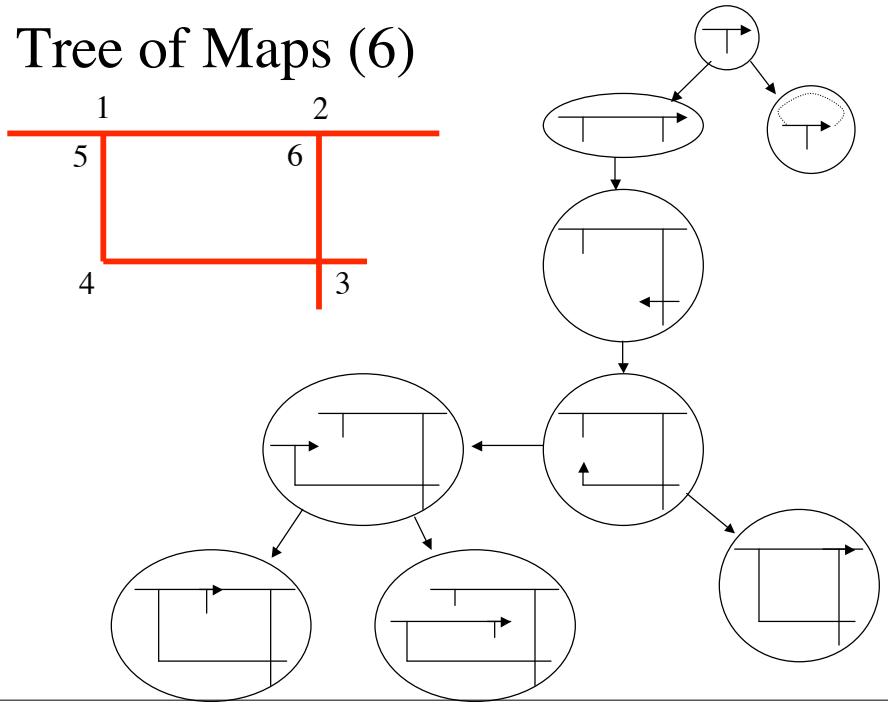




Tree of Maps (5)



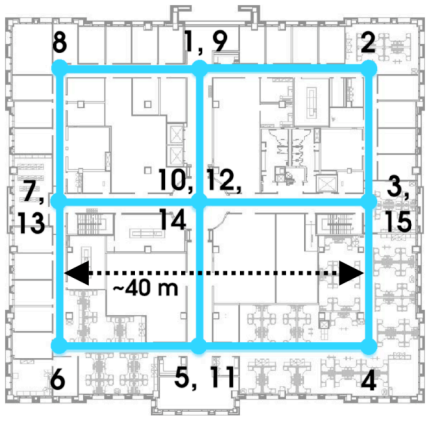
Tree of Maps (6)

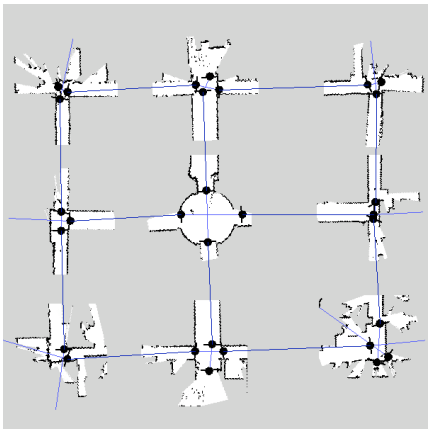


Find the Current Best Map

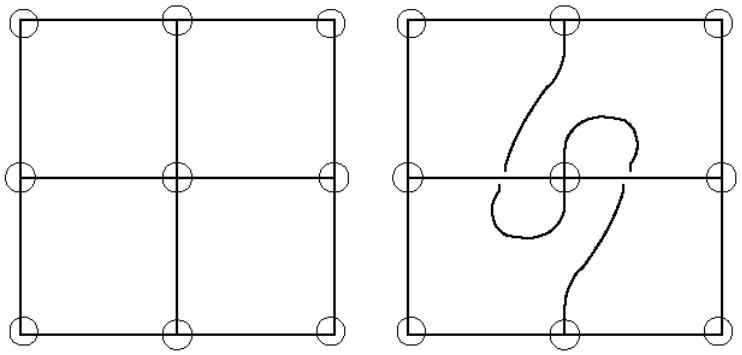
- The tree is **guaranteed** to contain the true map
  - All consistent maps are created.
  - Only inconsistent ones are deleted.
- Rank the consistent maps by simplicity and likelihood.
  - Each map is a loop-closing hypothesis.
  - The true map is often simpler than the others.
- Use the current best map for planning.
  - Remember the tree.
  - The current best map could be refuted.

The Topological Map Links Local Place Maps





Bizarre Map Hypotheses Ruled Out By Topology, Planarity, & Probability



Result: Single correct topological map hypothesis

Next

- The Hybrid Spatial Semantic Hierarchy
- Building the global metrical map
  - Using the topological map as a skeleton