World Maps and Localization

15-494 Cognitive Robotics

David S. Touretzky &
Ethan Tira-Thompson

Carnegie Mellon

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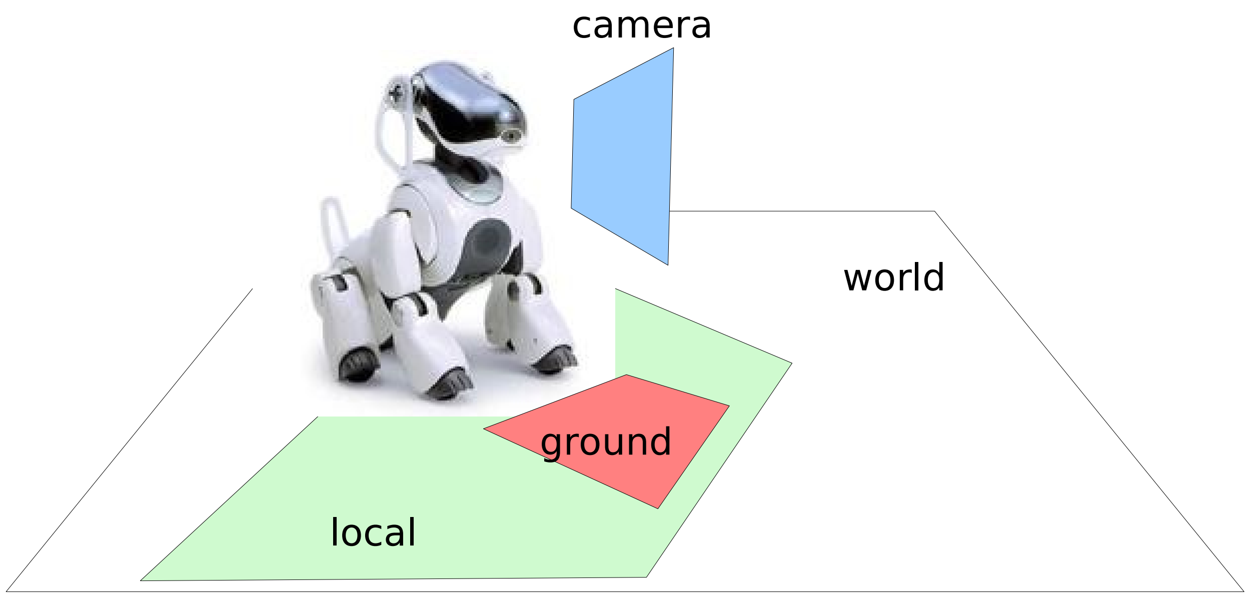
Frames of Reference



- Camera frame: what the robot sees.
- projectToGround() = kinematics + planar world assumption.
- Local map assembled from camera frames each projected to ground; robot moves head but not body.
- World map assembled from local maps built at different spots in the environment.

Four Shape Spaces

- camShS = camera space
- groundShS = camera shapes projected to ground plane
- localShS = body-centered (egocentric space);
  constructed by matching and importing shapes from groundShS
- worldShS = world space (allocentric space);
  constructed by matching and importing shapes from localShS
- The robot is explicitly represented in worldShS

Deriving the Local Map

1) `MapBuilder` extracts shapes from the camera frame
   - Use a request of type MapBuilderRequest::cameraMap if you want to stop here and just get camera-space shapes.

2) MapBuilder does projectToGround()
   - Use MapBuilderRequest::groundMap if you want to stop here and just get ground shapes from the current camera frame.

3) MapBuilder matches ground shapes against local shapes.
   - Request type should be MapBuilderRequest::localMap

4) MapBuilder moves to the next gaze point and repeats.
   - The world is assumed not to change during this process.

Deriving the World Map

- The *local* map covers only what the robot can see from a single viewing position.
- The *world* map can cover much larger territory.
  - Use MapBuilderRequest::worldMap
- The world map persists over a long time period.
  - The world will change. Updates must be possible.
- We update the world map by:
  - Constructing a local map.
  - Aligning it with the world map
  - Importing shapes from the local map.
  - Noting additions and deletions since the last local map match.

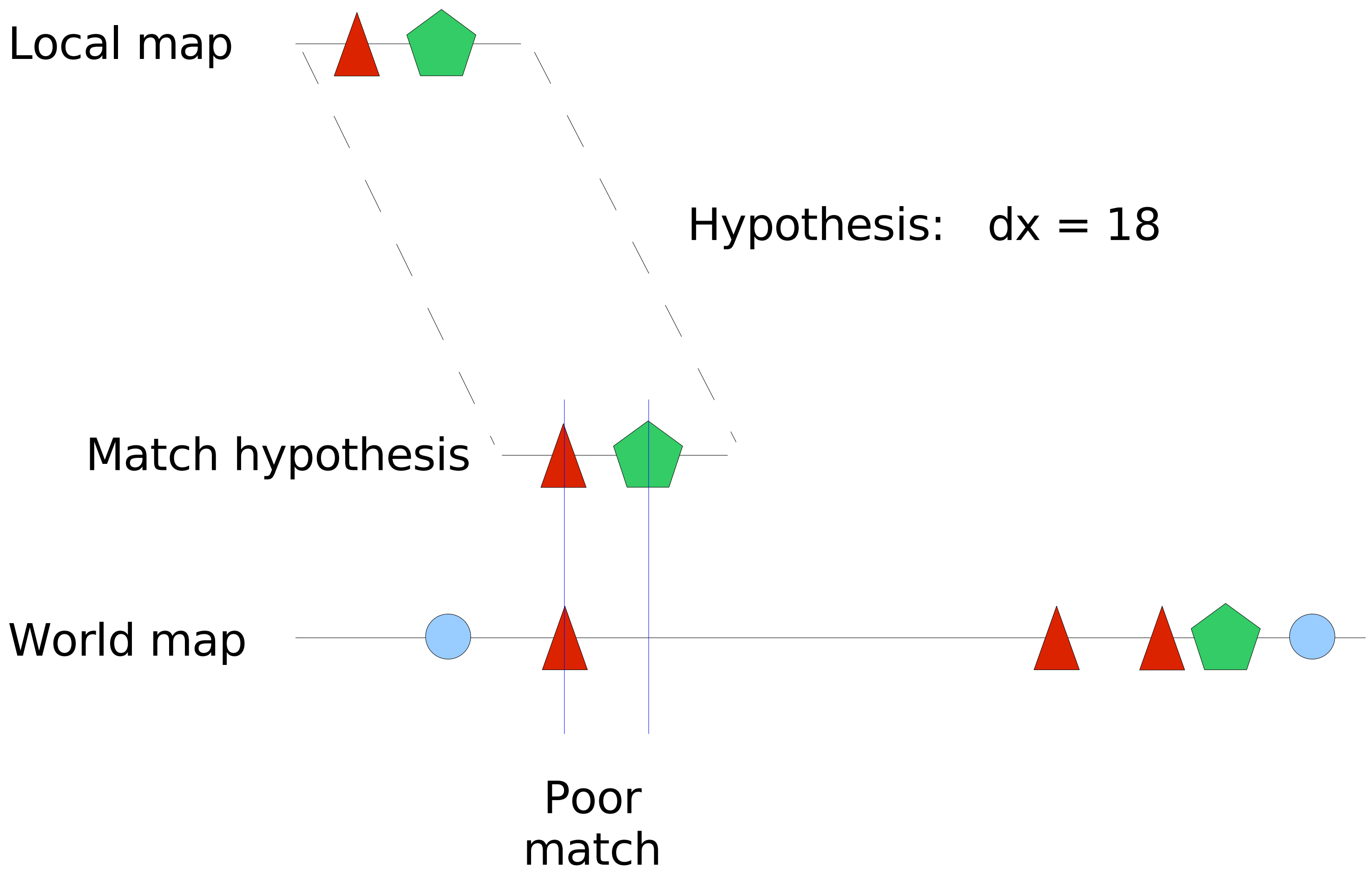
Localization

- How do we align the local map with the world map?
- This turns out to be equivalent to determining our position and orientation on the world map.
- Tricky, because:
  - The local map is noisy
  - The environment can be ambiguous (multiple pink landmarks)
- Sensor model: describes the uncertainty in our sensor measurements.
  - Can mix sensor types (vision, IR), info types (bearing, distance)

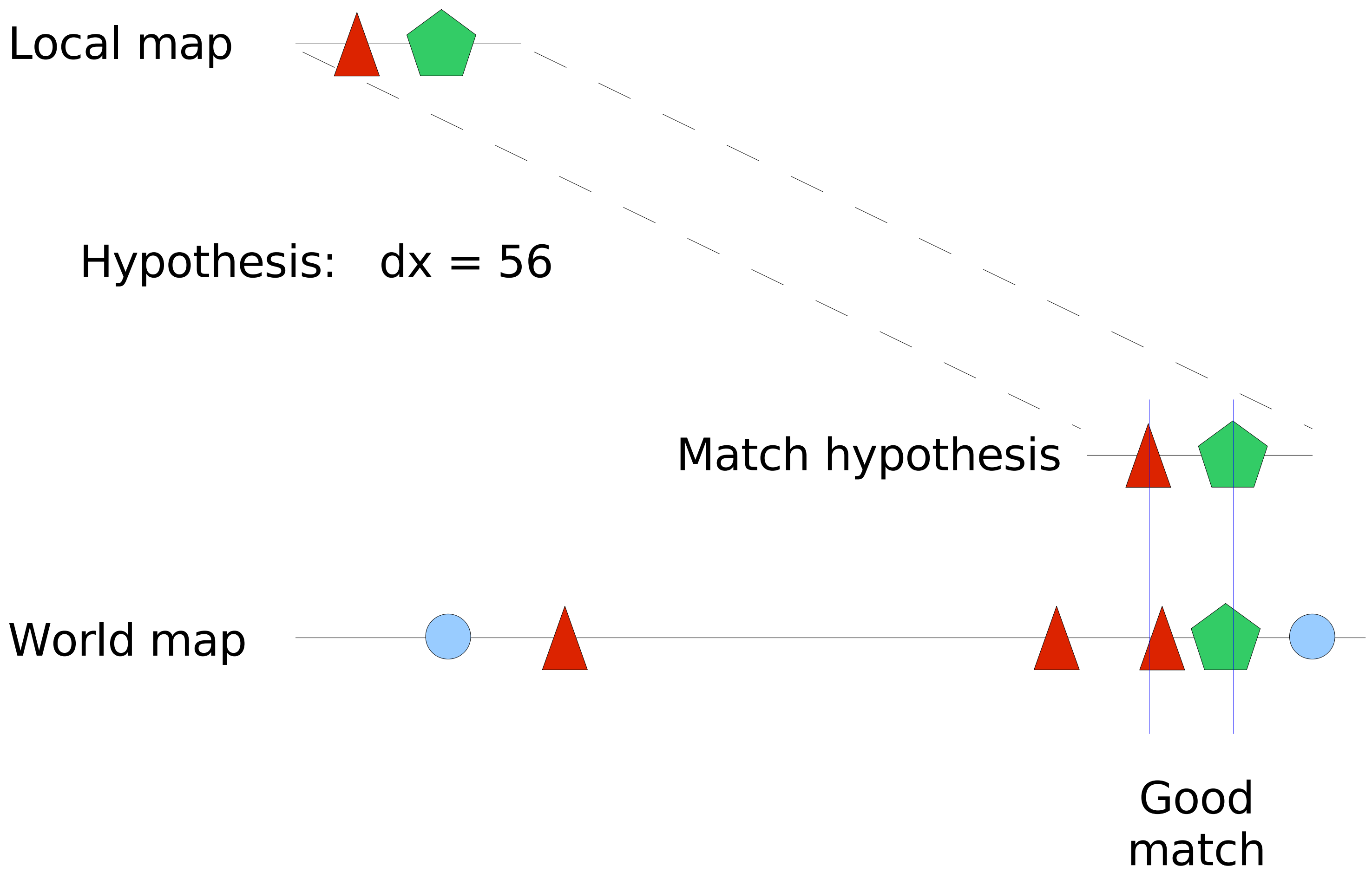
Particle Filtering

- A technique for searching large, complex spaces.
- What is the hypothesis space we need to search?
  - Robot's position (x,y)
  - Robot's orientation θ
- Each particle encodes a point in the hypothesis space.
- How can we evaluate hypotheses?
  - Use sensor model to update particle weights

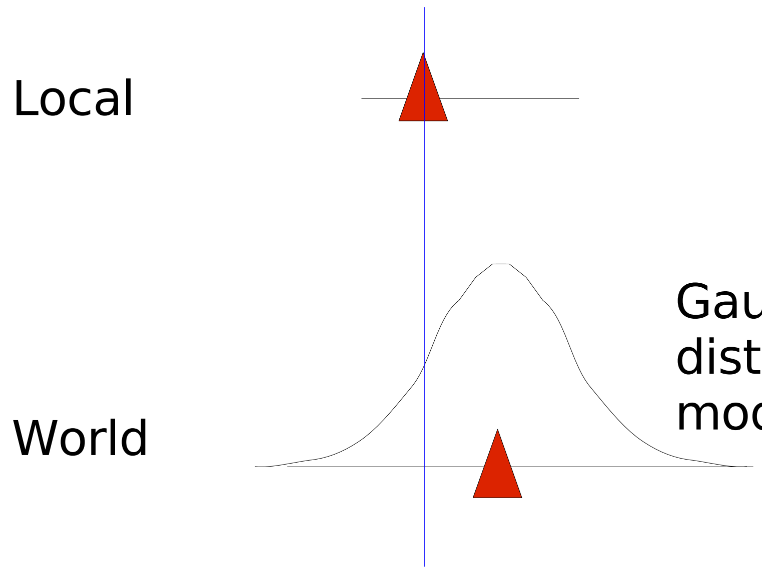
Ranking a Particle: 1-D Case



Ranking a Particle: 1-D Case

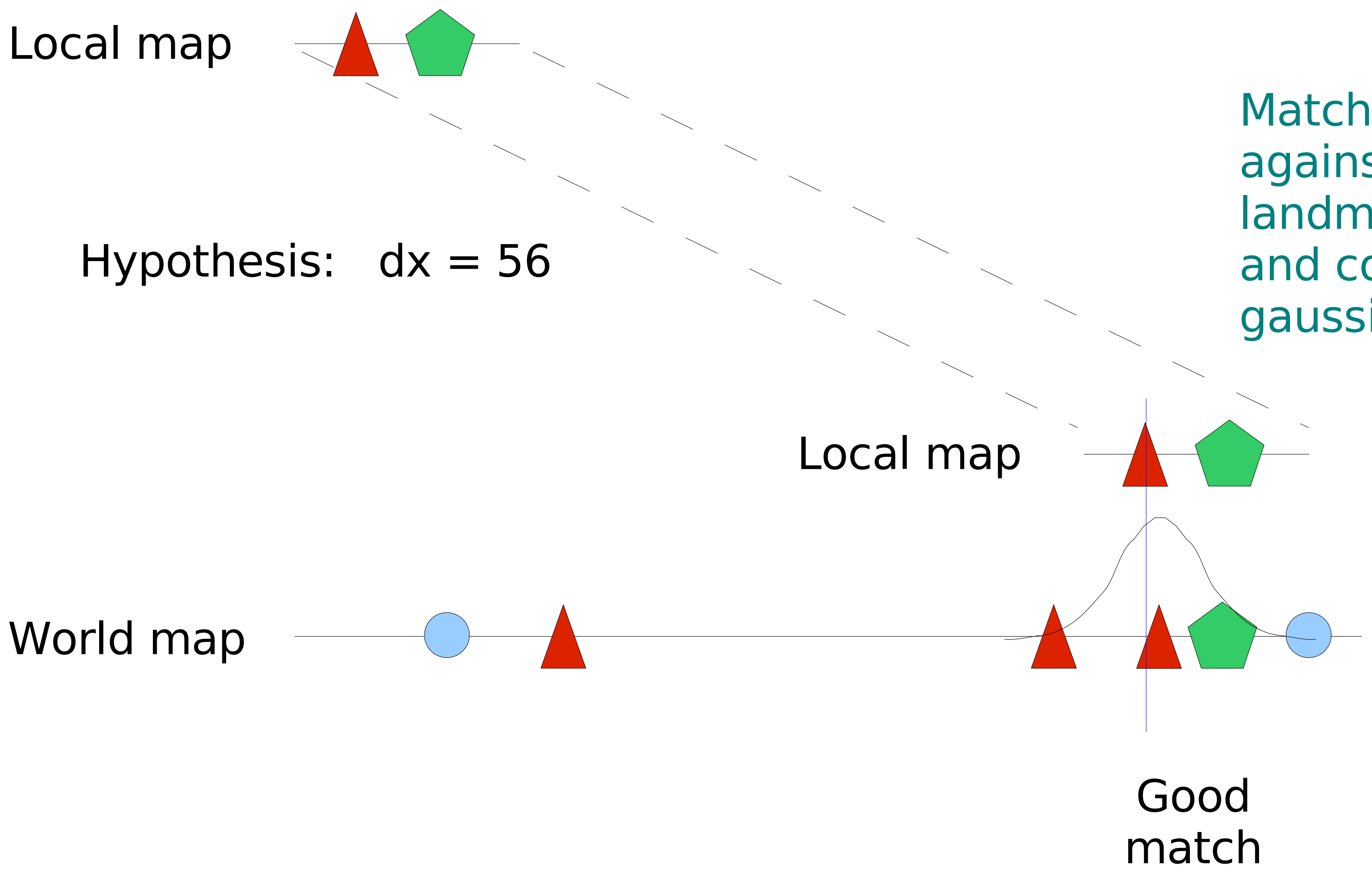


Matching a Landmark



Gaussian probability distribution: a sensor model

Pick the Best Candidate

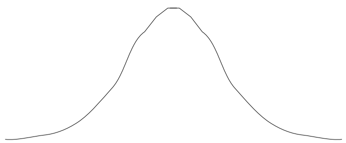


Match each local landmark against the <u>closest</u> world landmark of the same type and color. Score with a gaussian.

Matching a Set of Landmarks

- Take the product of the match probabilities of the individual landmarks:

$$G(x, x_0) = \exp\left[\frac{-(x - x_0)^2}{\sigma^2}\right]$$



$$P(s \in L, t \in W | h) = G(L.s + h, W.t)$$

$$P(s \in L | W, h) = max_{t \in W} P(s \in L, t \in W | h)$$

$$P(h) = \prod_{s \in L} P(s | W, h)$$

L.s = coordinate of shape s in Local map

W.t = coordinate of shape t in World map

h = location hypothesis

- Allow penalty terms for addition, deletion.

Use Log Probabilities

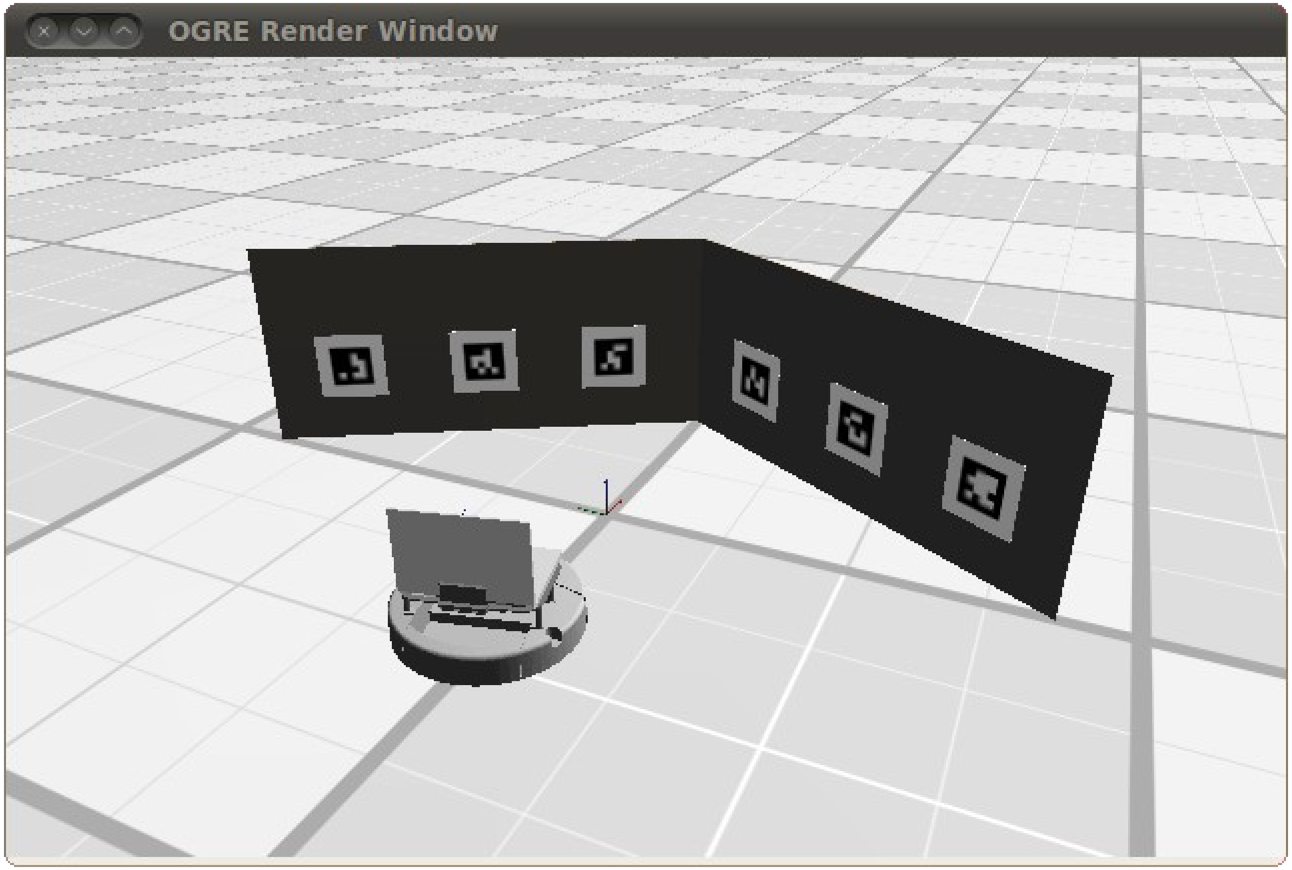
- Multiplying lots of small numbers can lead to floating point underflow.
- Mathematical trick: we can replace a product of probabilities by a sum of log probabilities.

$$P(h) = \sum_{s \in L} \log P(s|h, W)$$

- The result will be a negative number. The more negative the sum, the smaller the product. So the “best” hypothesis is still the one with the <u>maximum</u> score, whether we're using products or sums of logs.

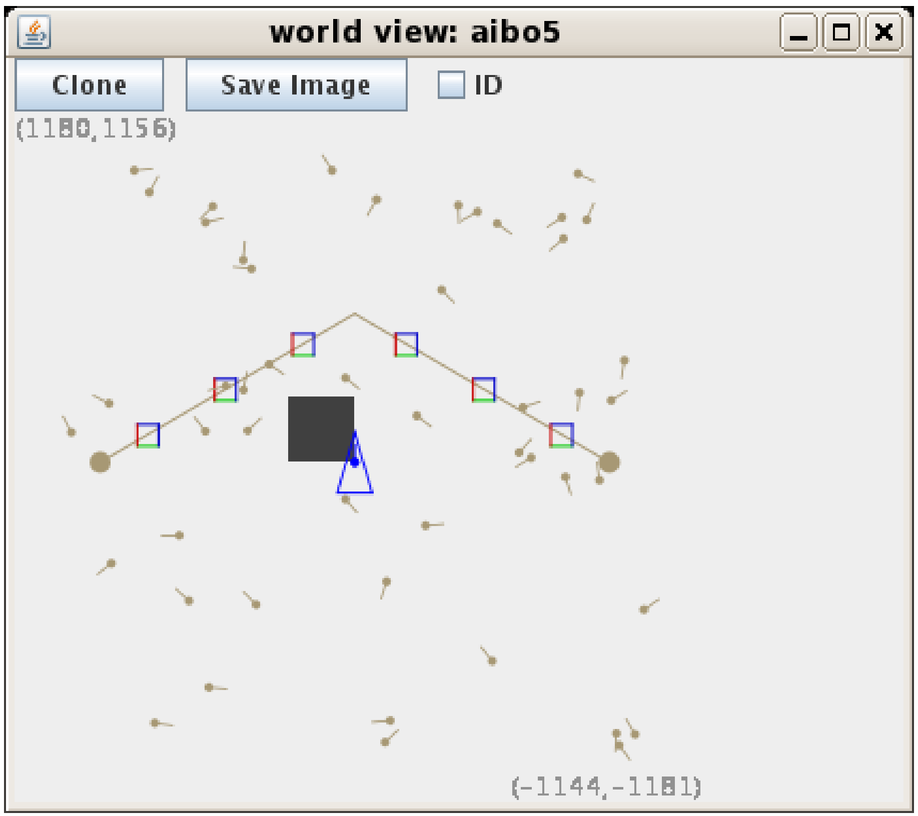
VeeTags Demo

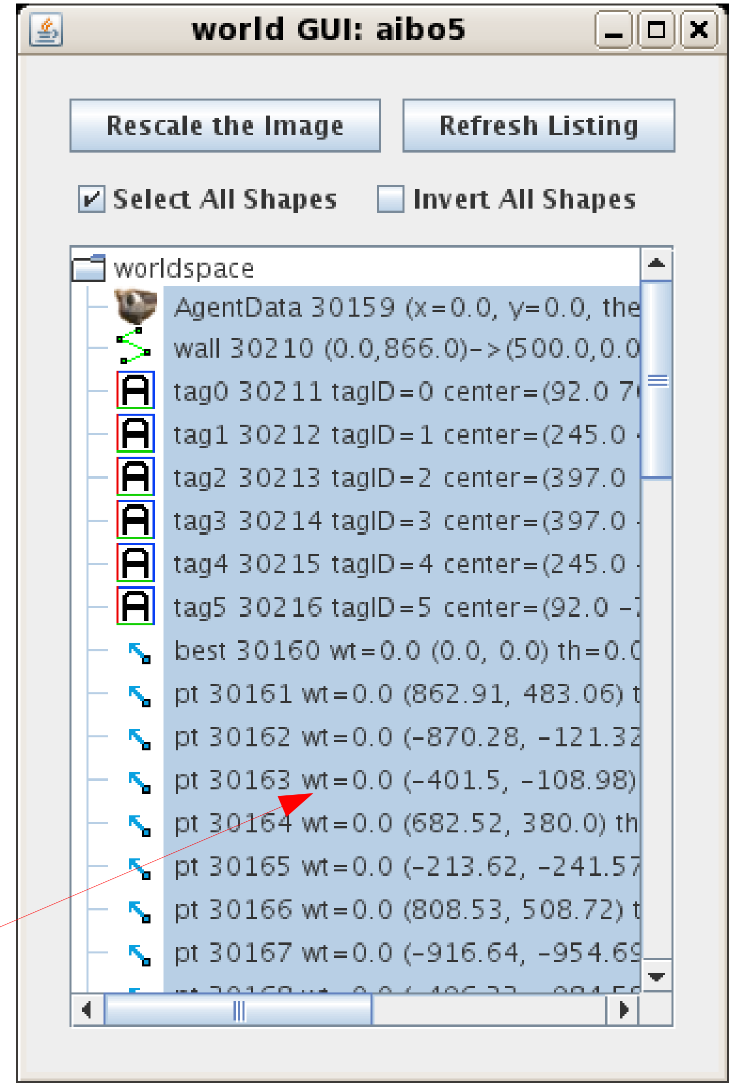
- Root Control > Framework Demos > Navigation Demos > VeeTags



Initial Location Unknown

- 2000 random particles (100 shown)

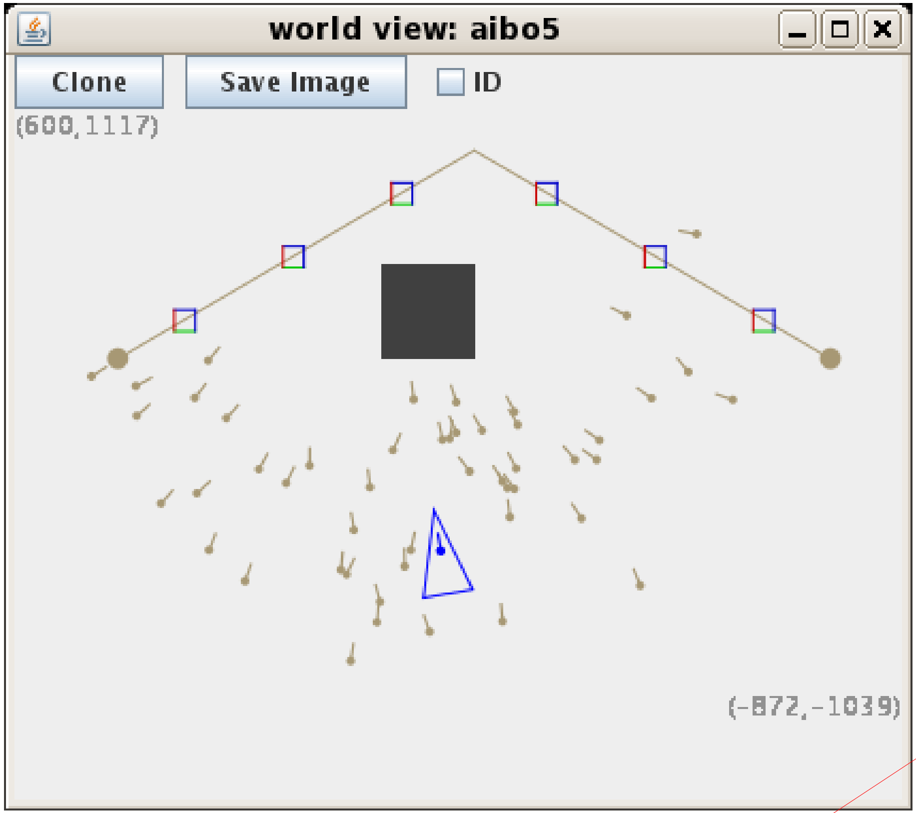


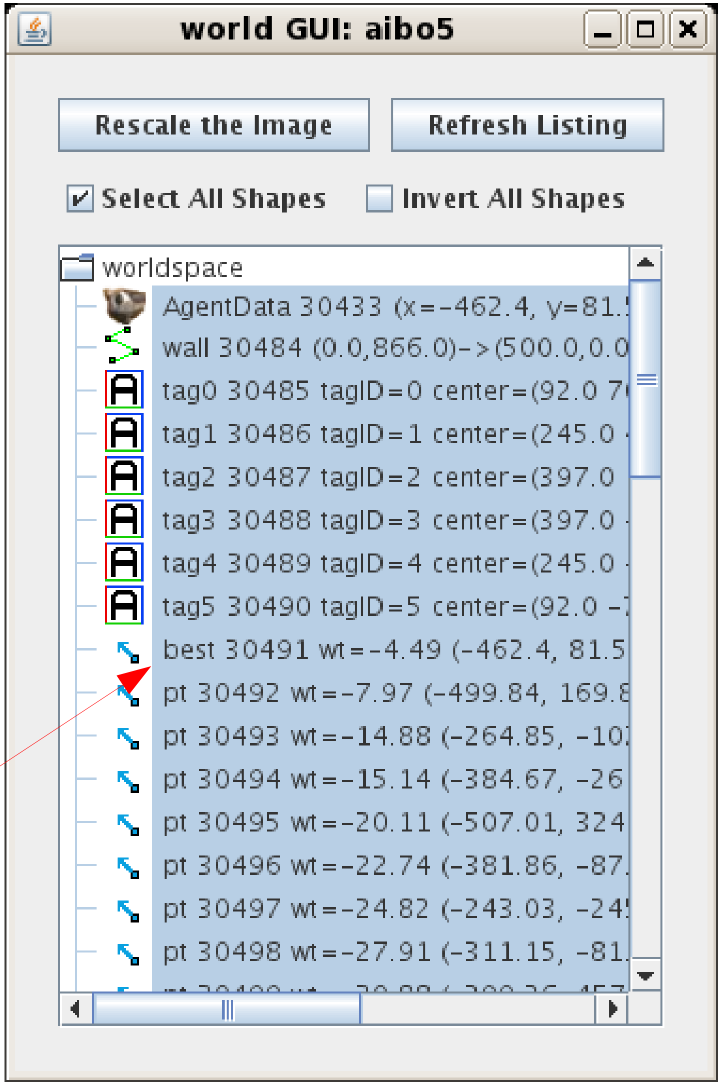


All weights initially 0.0

Localize Using AprilTags

- Displays the 100 best scoring particles



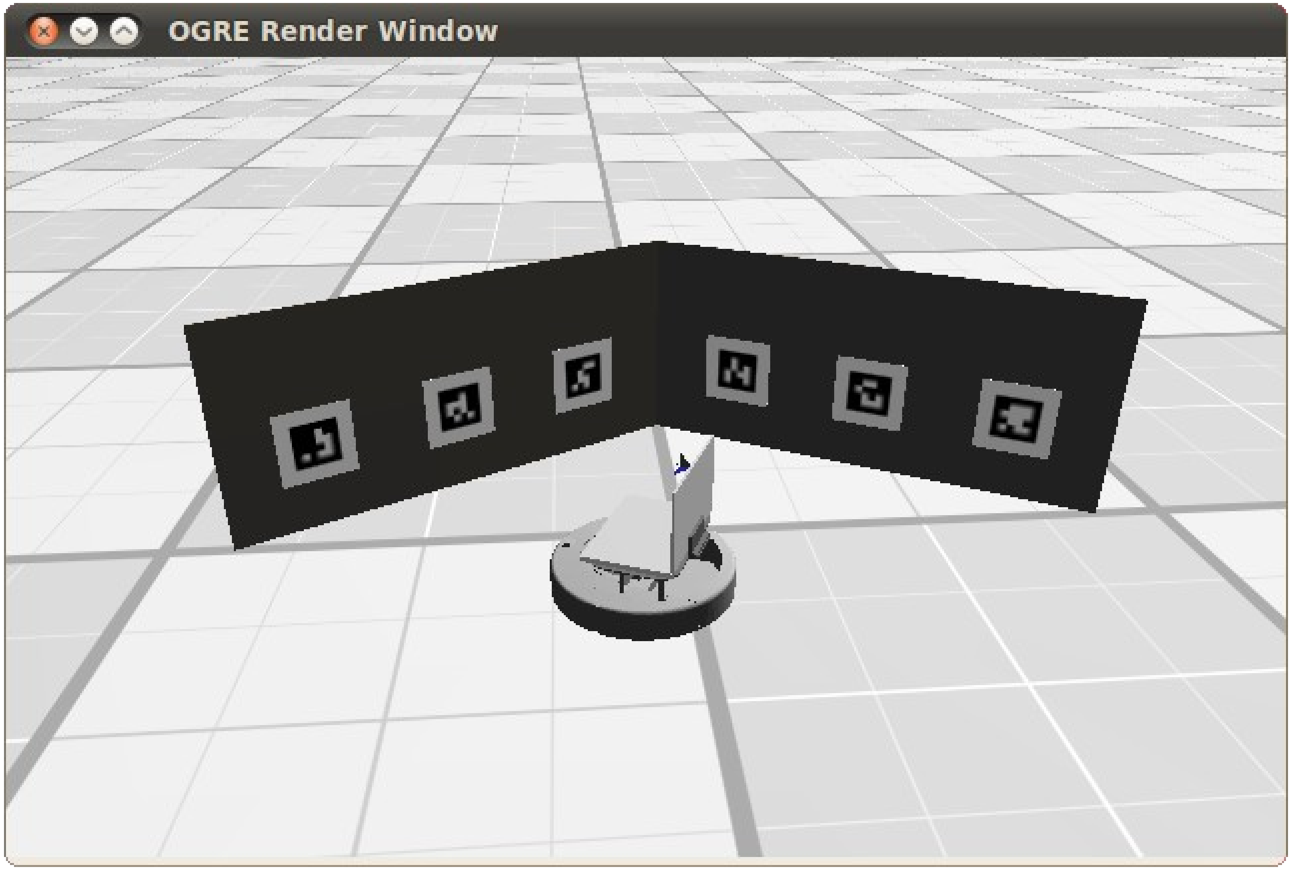


Best score -4.49

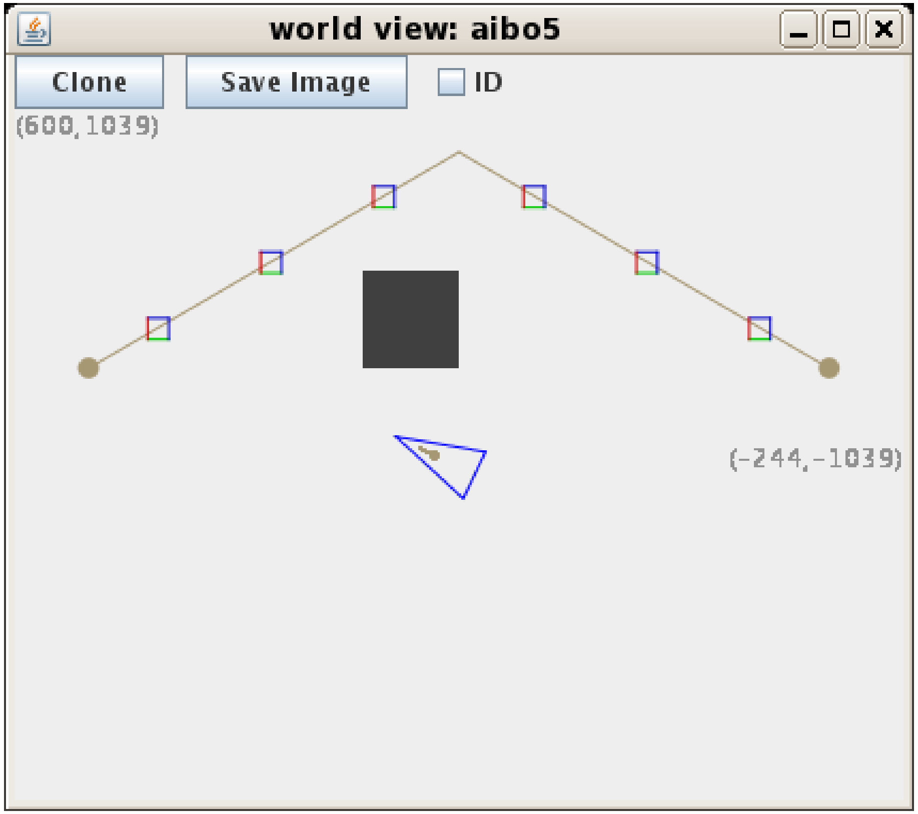
Importance Sampling

- For each particle h, calculate the probability P(h)
- Create a new generation of particles by resampling from the previous population:
  - Particles with high probability should be more likely to be sampled, and will therefore multiply.
  - Particles with low probability likely won't be sampled, and will therefore probably die out.
- The new particles' parameters are “jiggled” a little bit. This is how we search the space.
- Repeat this resampling process for several generations.

Move To New Position



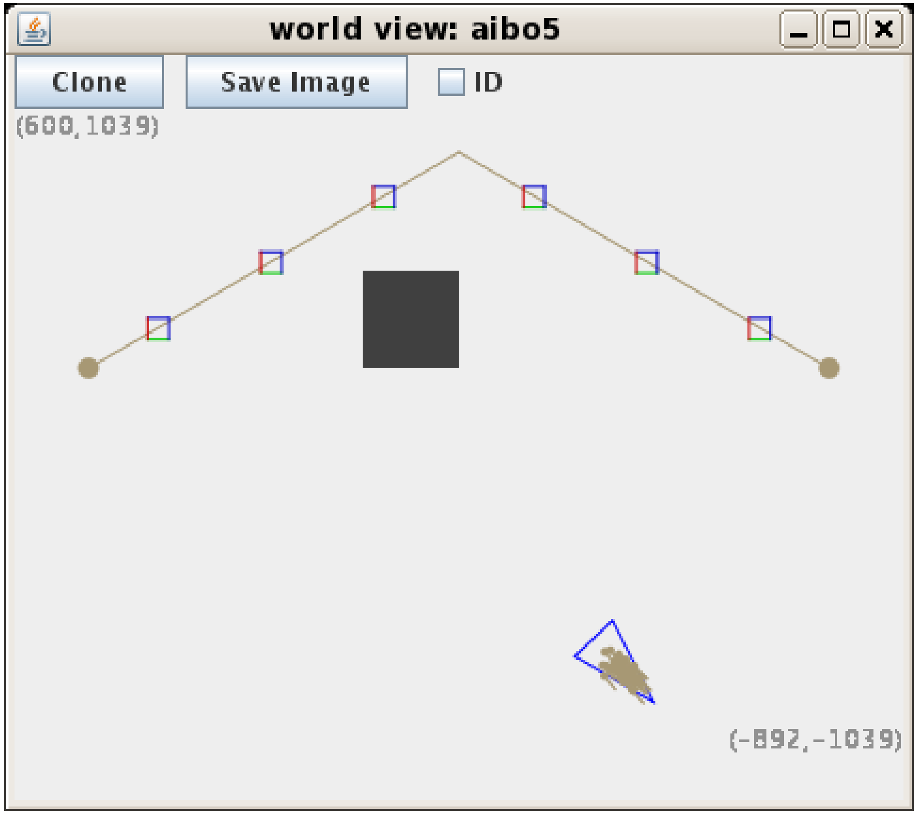
Resample and Localize Again



Particle cloud collapses to a tightly packed cluster.

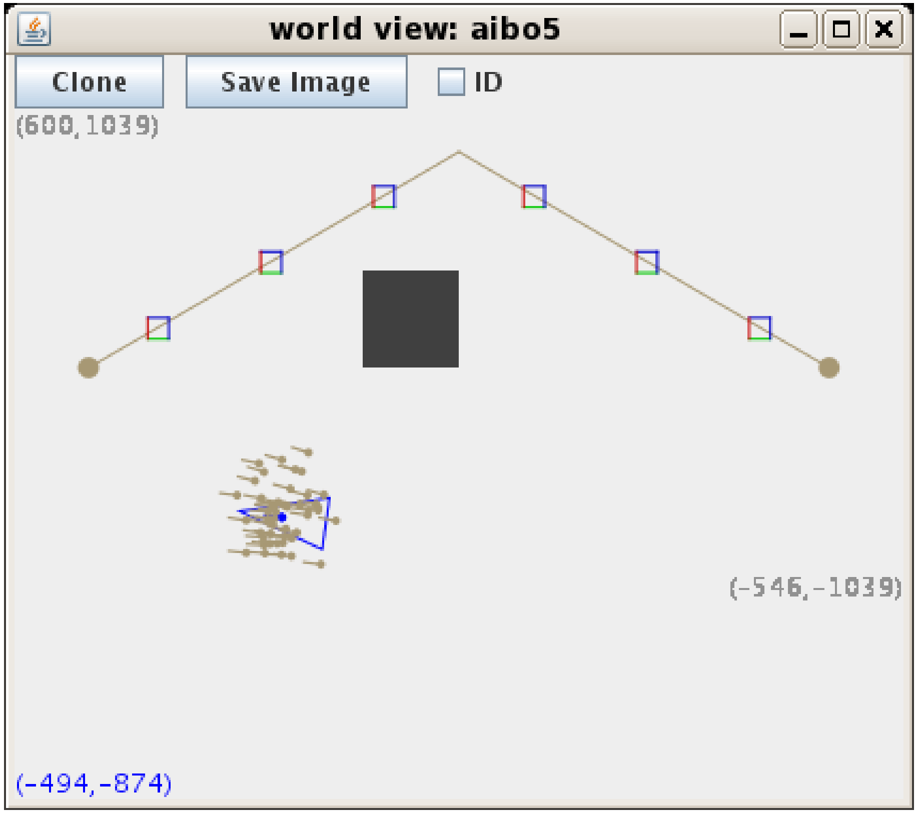
Odometry

- Use odometry to update the robot's position between localization steps.
- Drag the particles along as the robot moves, but add noise to reflect uncertainty in the motion model.



Uncertainty Grows With Motion

- Particle cloud expands as noise accumulates.

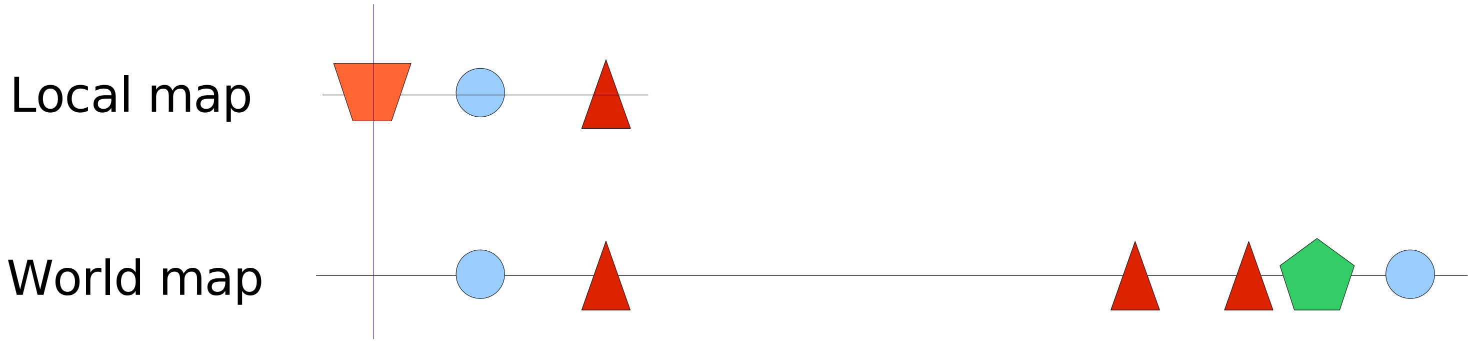


SLAM

- Simultaneous Localization and Mapping
- When is this necessary?
  - When we don't know the map in advance.
  - When the world is changing (landmarks can appear or disappear, or change location.)
  - When we're moving through the world.
- How do we localize on a map that we are still in the process of building?
- Motion model: estimates (by odometry) our motion through the environment.

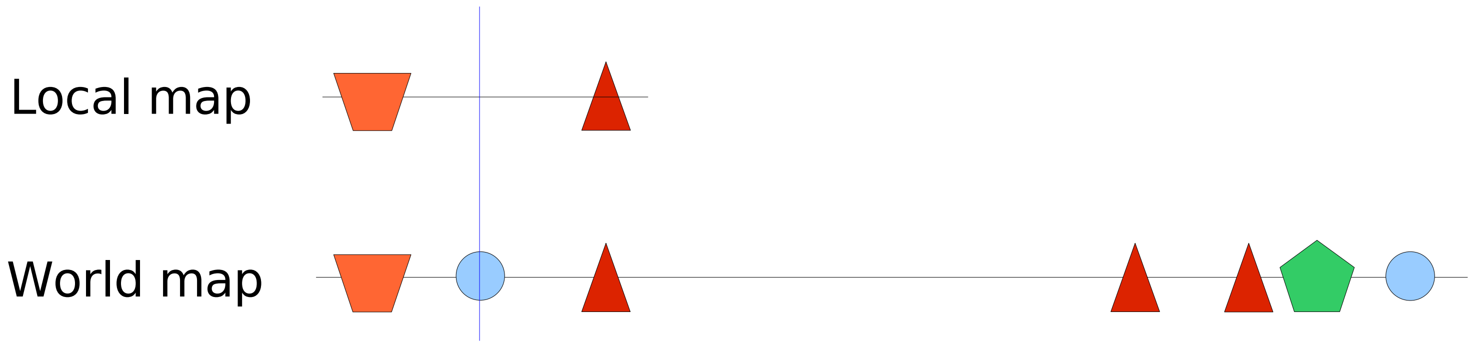
Addition Penalty

- A shape in the local map that isn't in the world map must be accounted for as an addition.
- Assess a penalty on P(h) for each addition, but remove that shape from the product term for P(h) so the product doesn't go to zero.



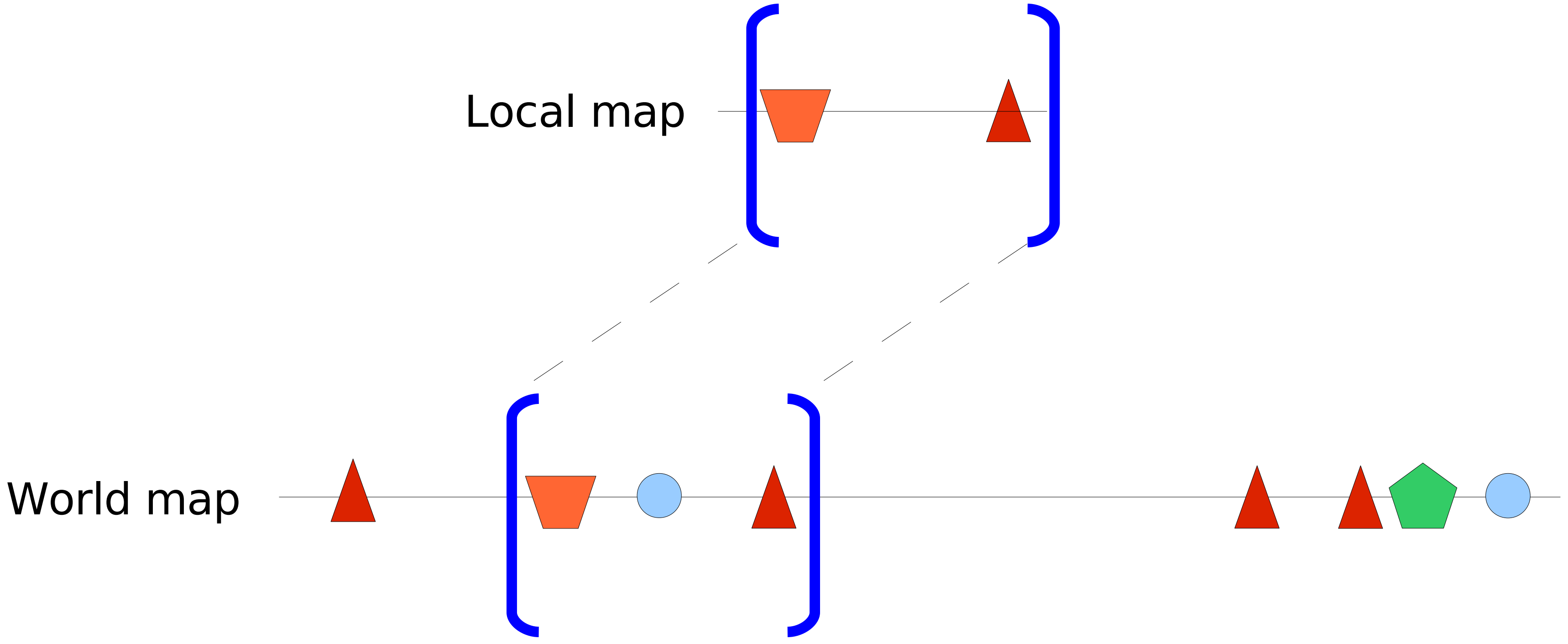
Deletion Penalty

- A shape in the world map that should be visible in the local map but isn't must be accounted for as a deletion.
- Assess a penalty on P(h) for each deletion, but remove that shape from the product term for P(h) so the product doesn't go to zero.



What Shapes Should be Visible?

- Take bounding box of shapes in local space.
- All shapes within that box should be visible in world space.



When Objects Move

- If an object moves only a little bit, it will still match, and the position will be updated.
- If an object moves by a larger amount, we'll get:
  - An object deletion at the old location
  - An object addition at the new location
- Could watch for this and combine both changes into a single “move” penalty.
- If h is a poor hypothesis, then every object will appear to have “moved”.

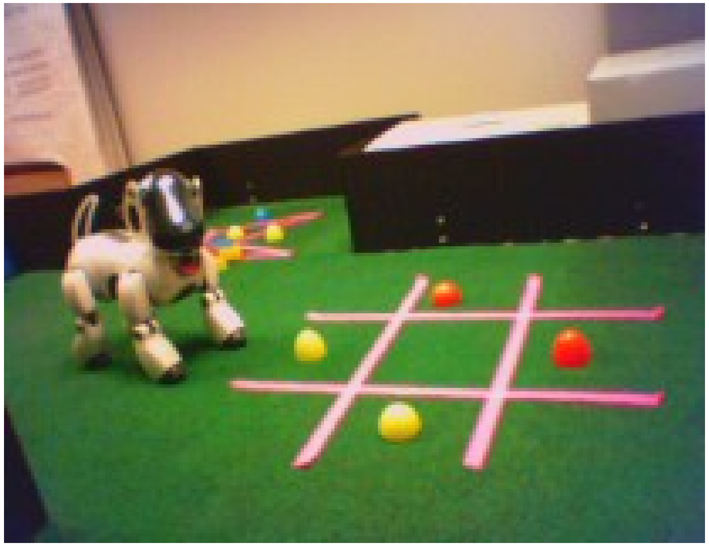
So What's In A SLAM Particle?

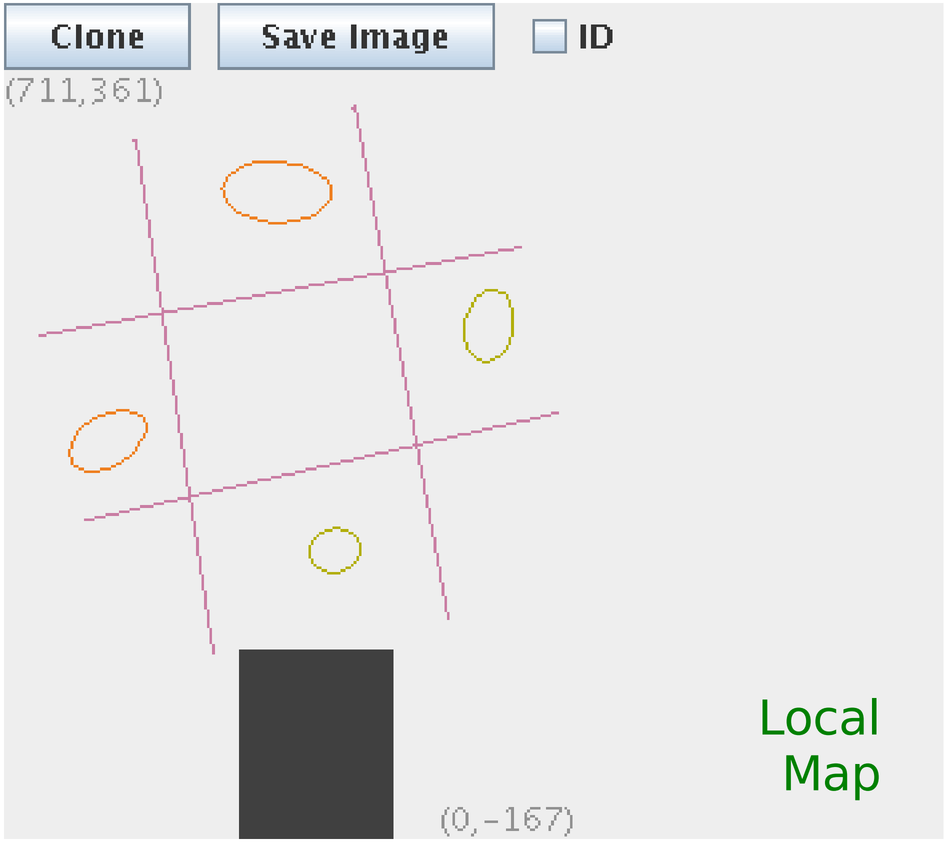
```
float dx, dy;

AngTwoPi orientation;

vector<bool> additions(numLocalShapes, false);

vector<bool> deletions(numWorldShapes, false);
```

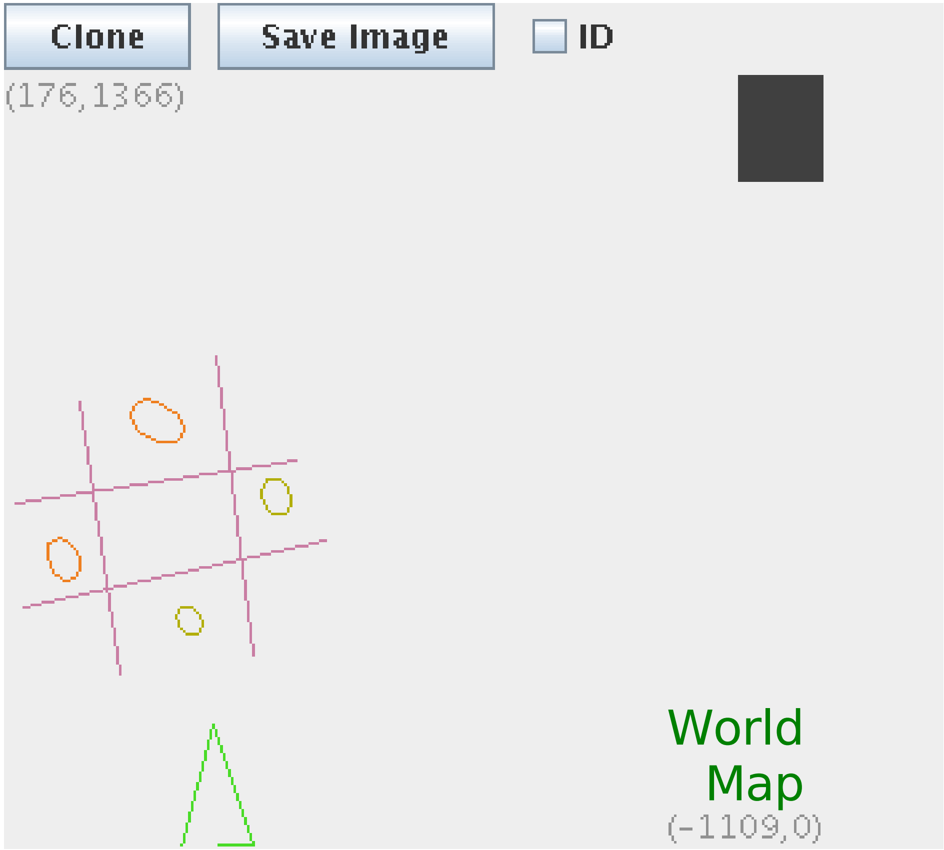
Parameters to adjust:

- Number of particles (2000)
- Amount of noise to add to dx, dy, θ
- Probability of flipping an add or delete bit

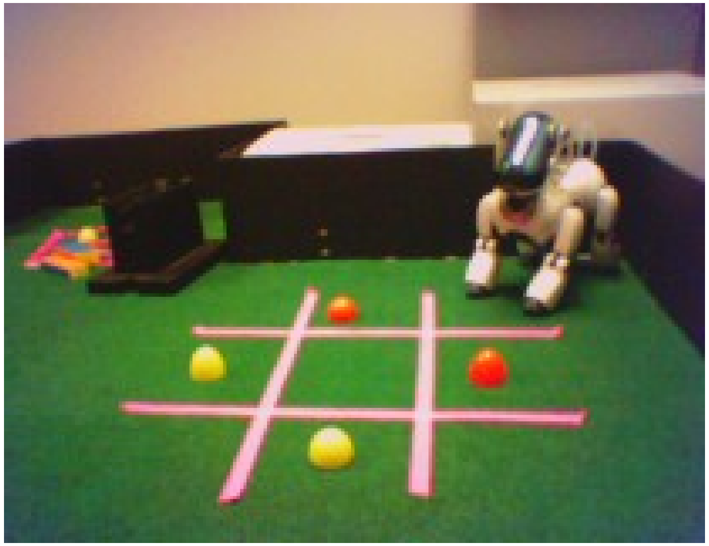
Local and World Maps on the Robot

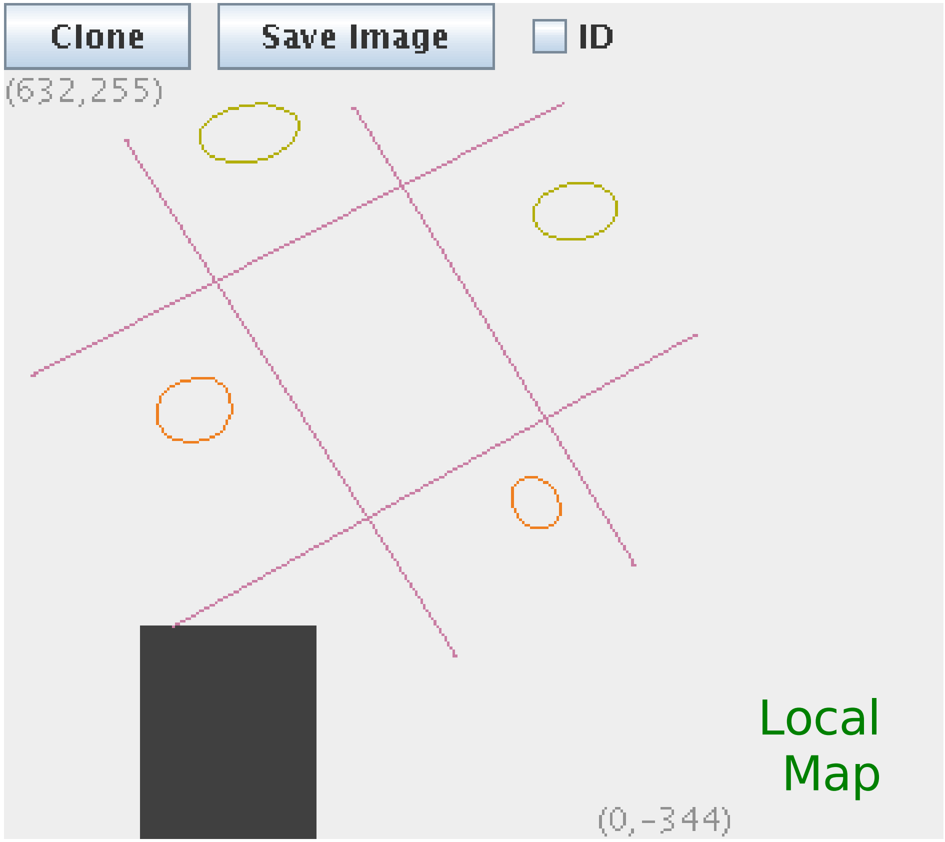


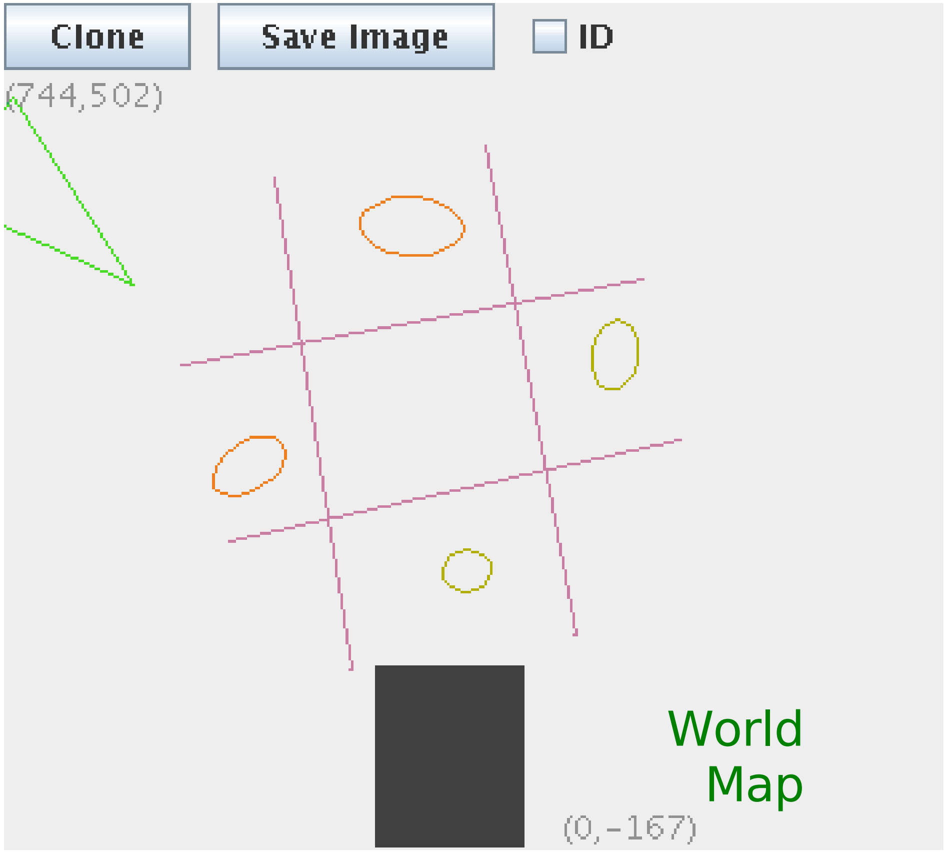




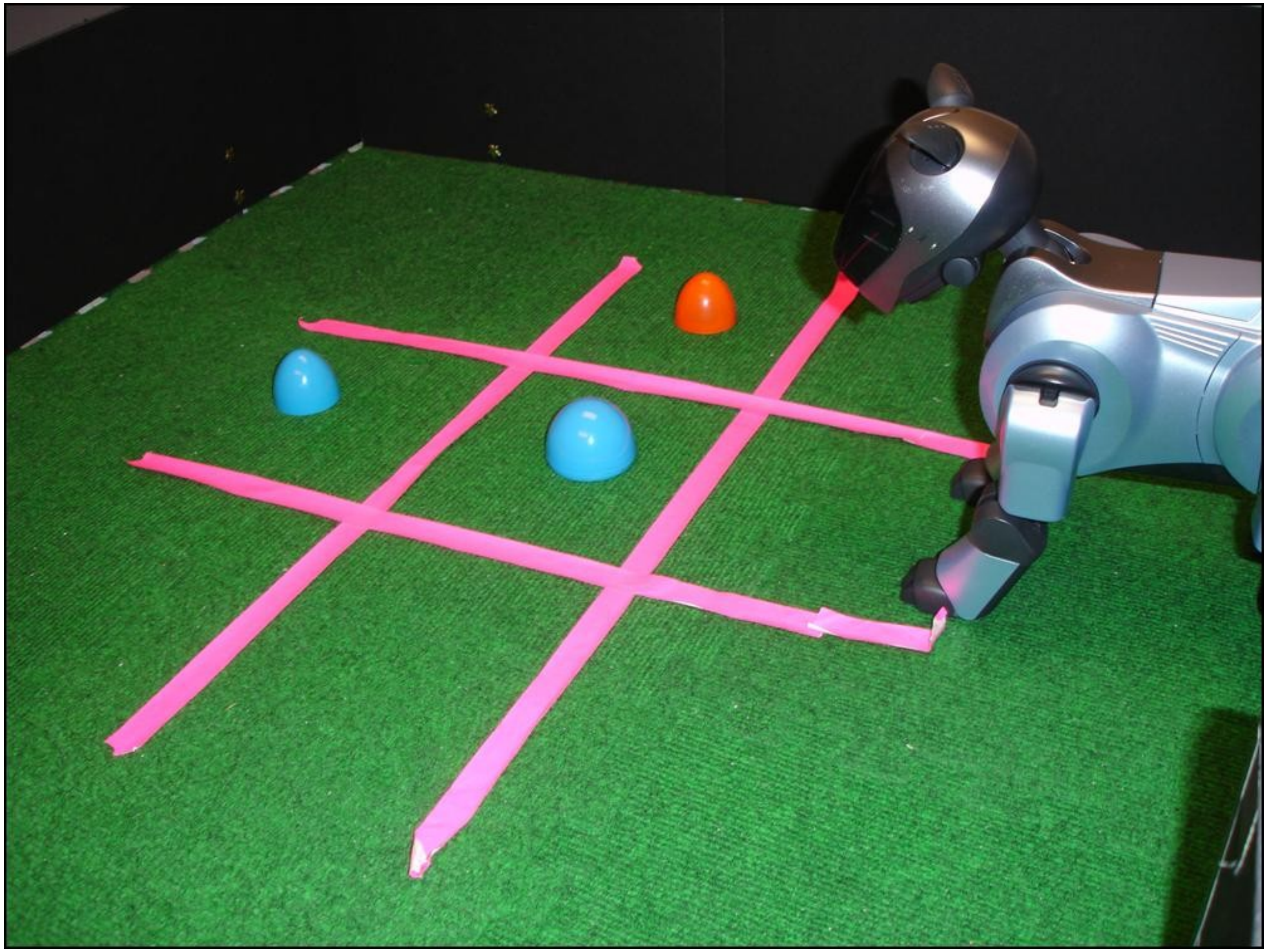
Localization After Movement

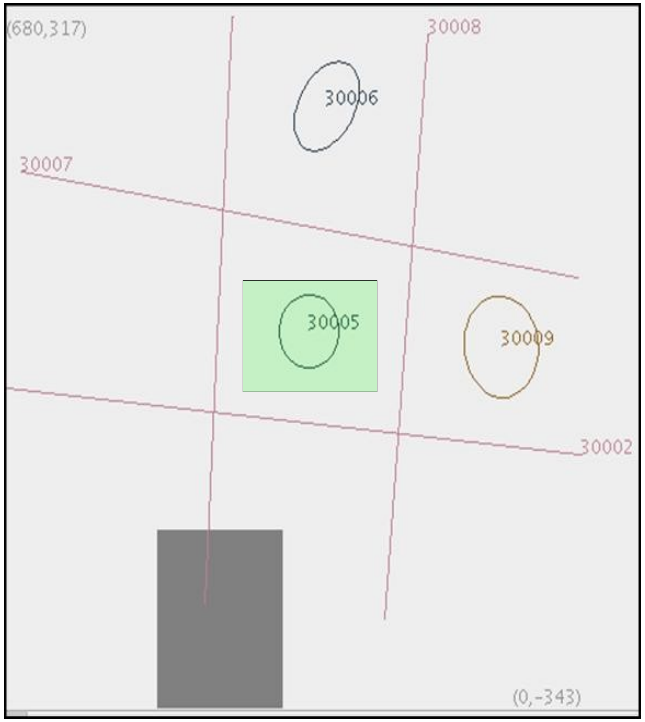






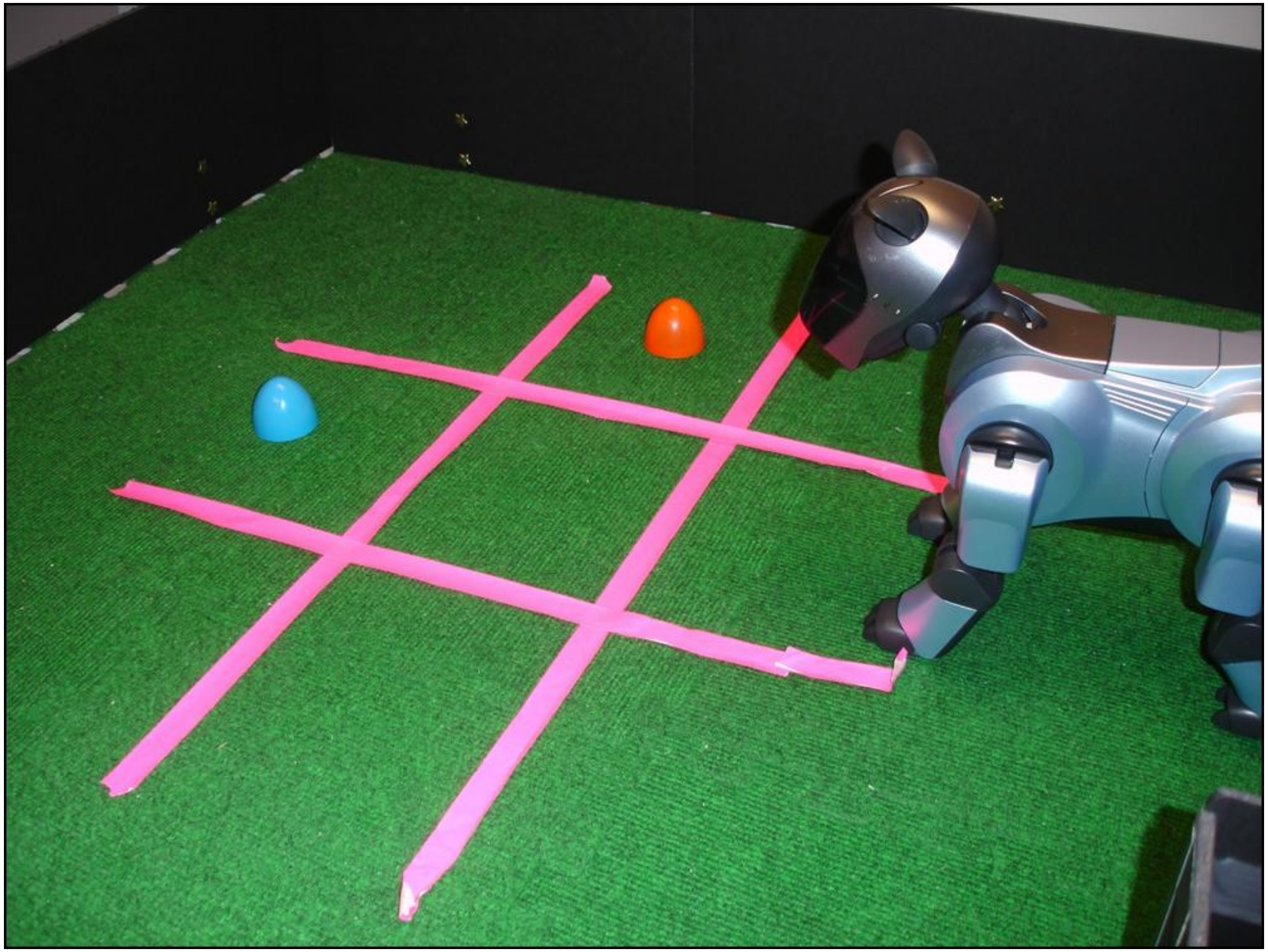
Construct World Map





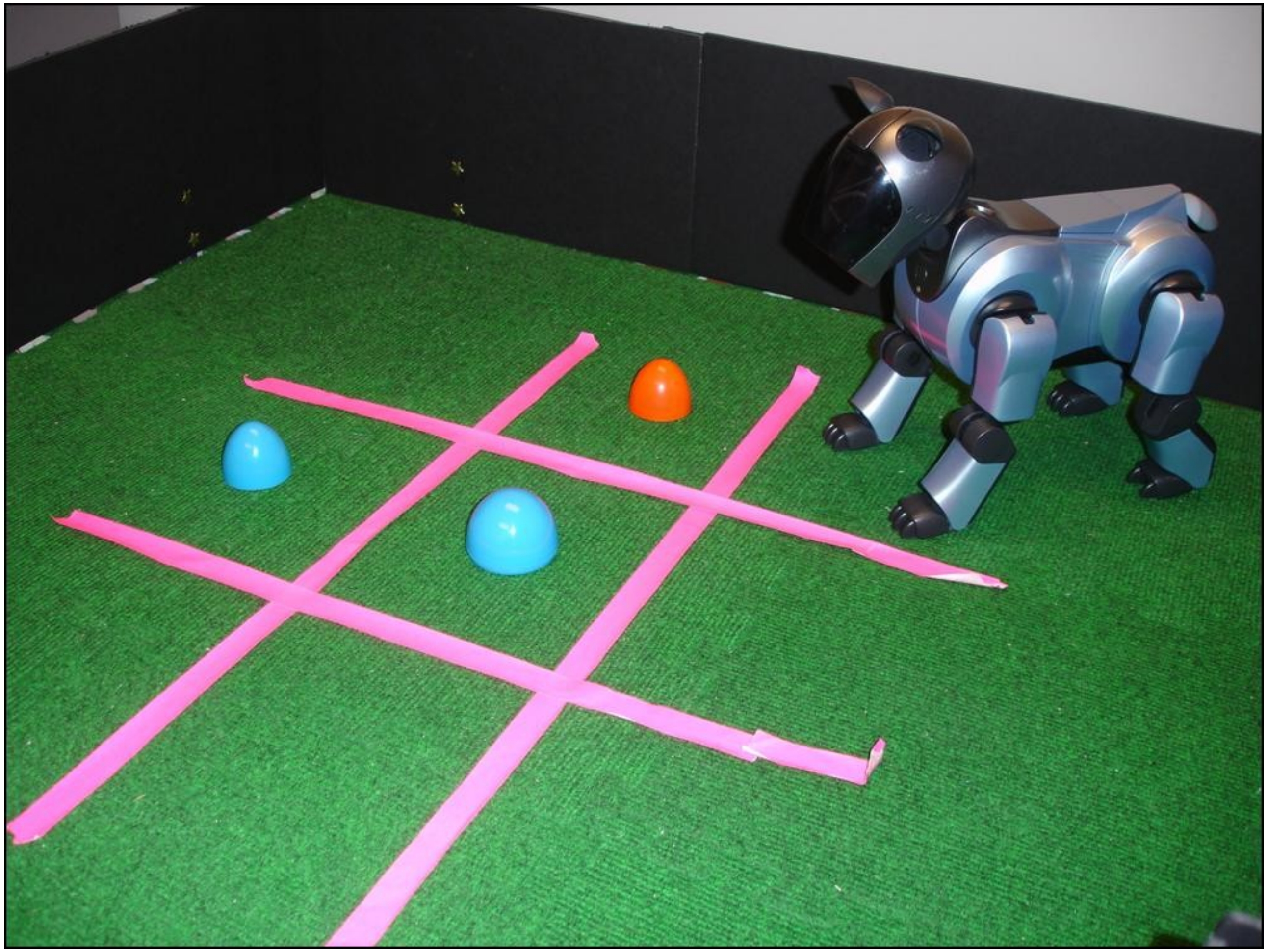
Three pieces on the board. Let's delete one.

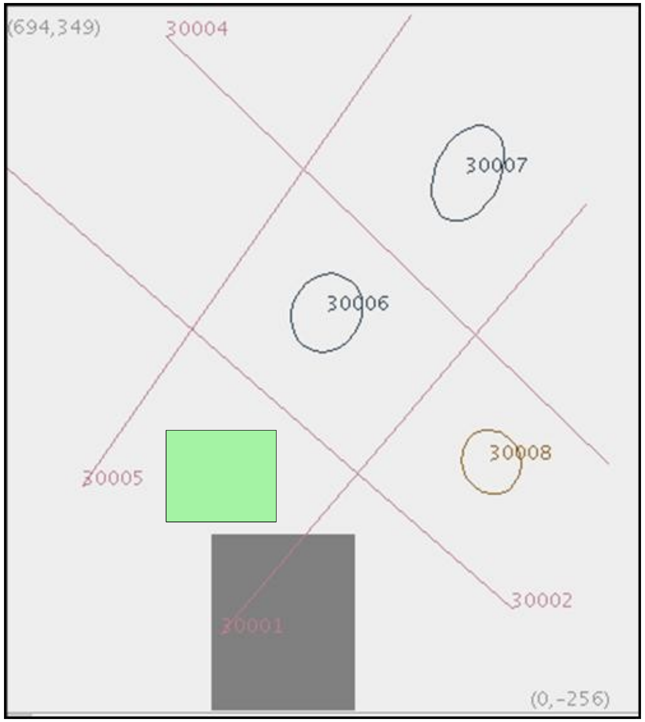
Delete a Game Piece



Actual change: dx = 0 mm, dy = 0 mm, θ = 0°, delete shape 30005
Particle filter: dx = 9 mm, dy = 13 mm, θ = -0.2°, delete shape 30005

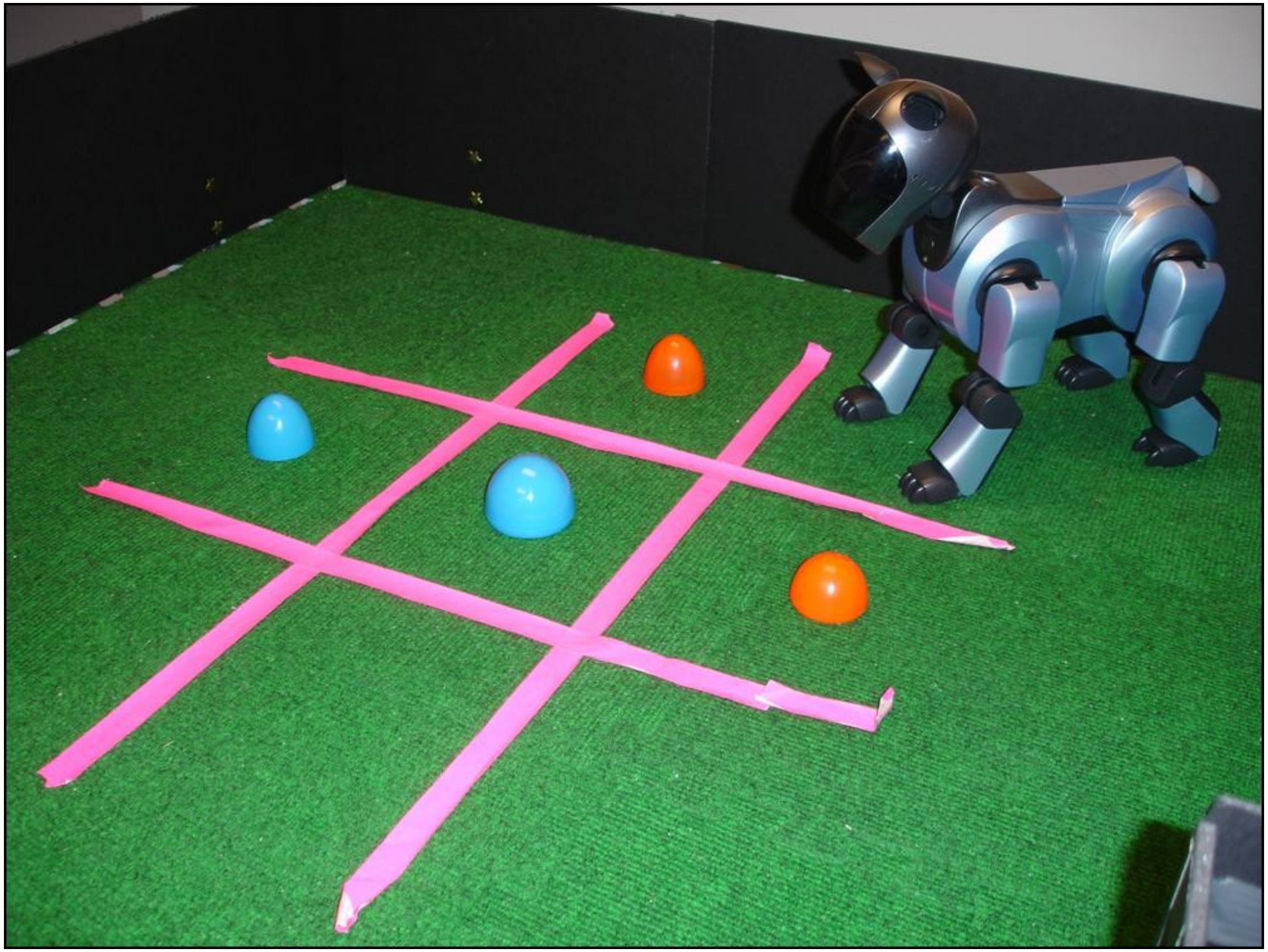
Construct World Map

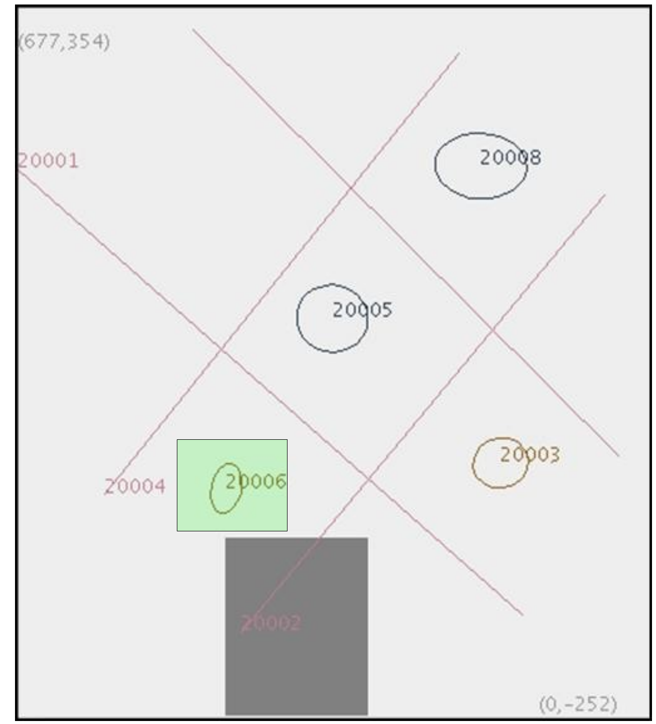




Three pieces on the board. Let's add one.

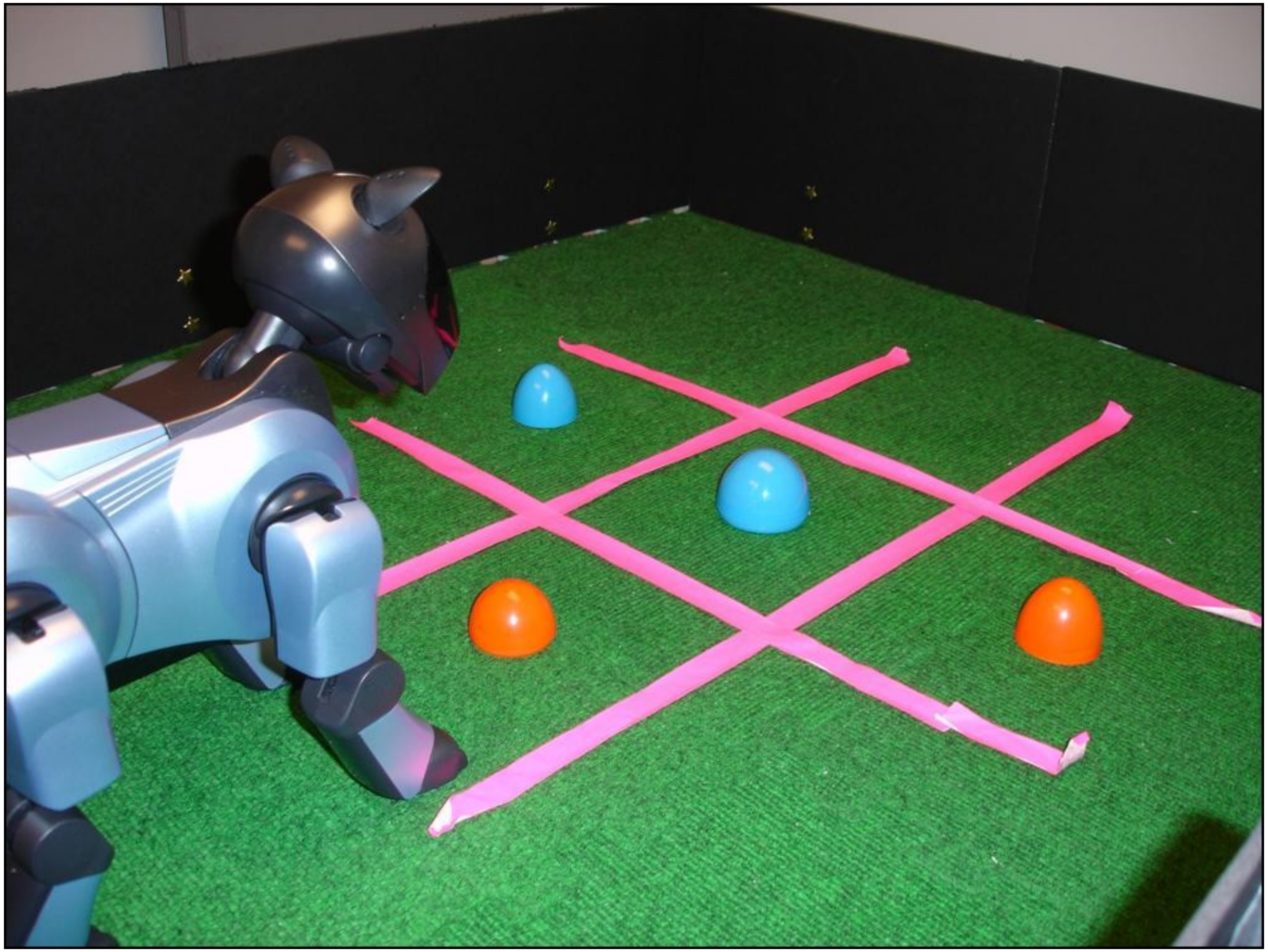
Add a Game Piece

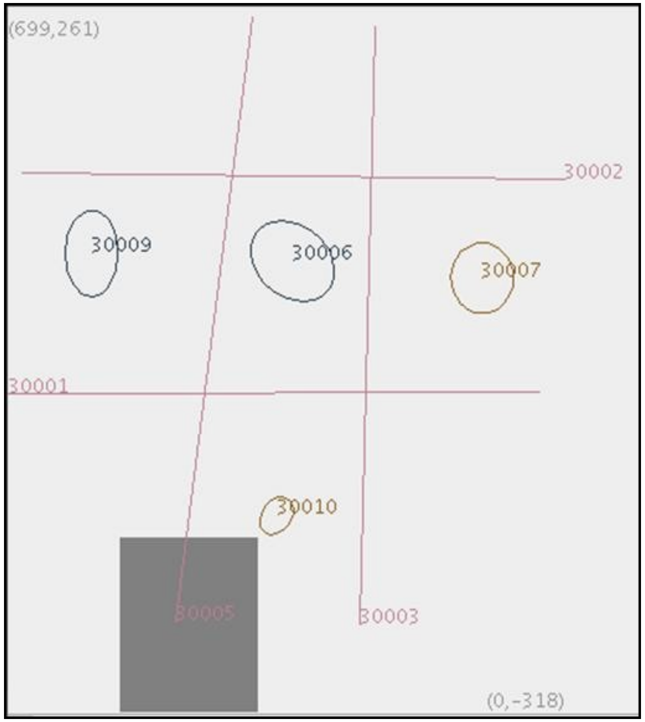




Actual change: dx = 0 mm, dy = 0 mm, θ = 0°, add shape 20006
Particle filter: dx = 2 mm, dy = -.5 mm, θ = -0.6°, add shape 20006

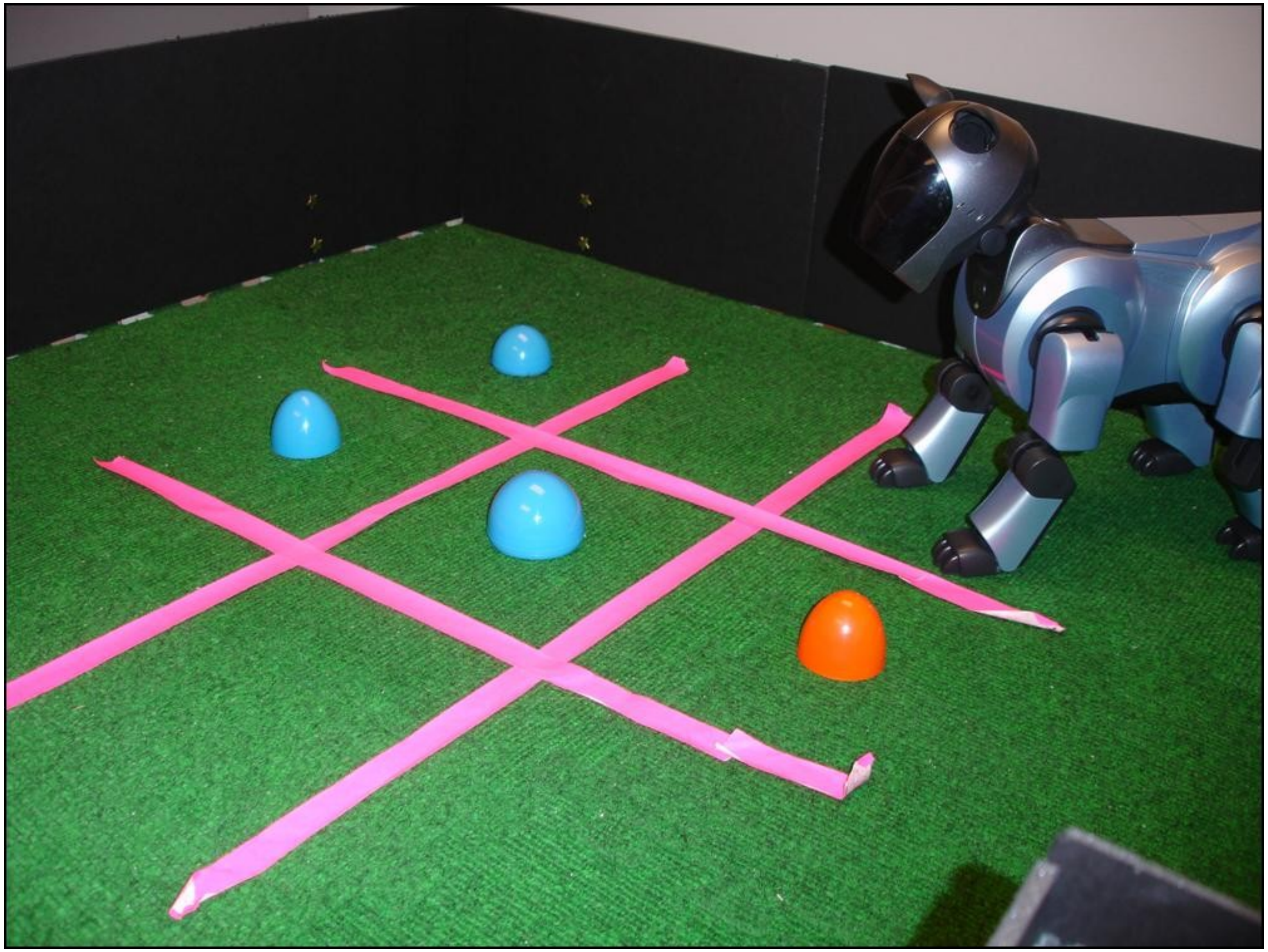
Construct World Map

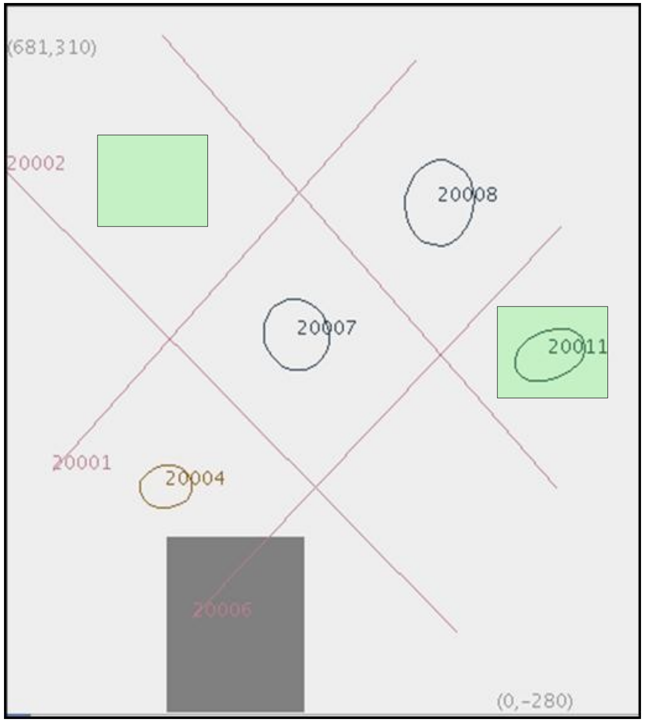




Four pieces on the board. Let's move, add, and delete.

Change Position and Add/Delete





Actual change: dx = 670 mm, dy = -260 mm, θ = 45°, add 20011, del. 30010
Particle filter: dx = 678 mm, dy = -306 mm, θ = 42°, add 20011, del. 30010

How To Do Localization

- The Pilot handles odometry and localization for you.
- It looks in the world shape space to find landmarks.
- To localize:

```
PilotNode($, PilotTypes::localize)
```

- The Pilot will localize automatically when it is navigating to a destination you specify.