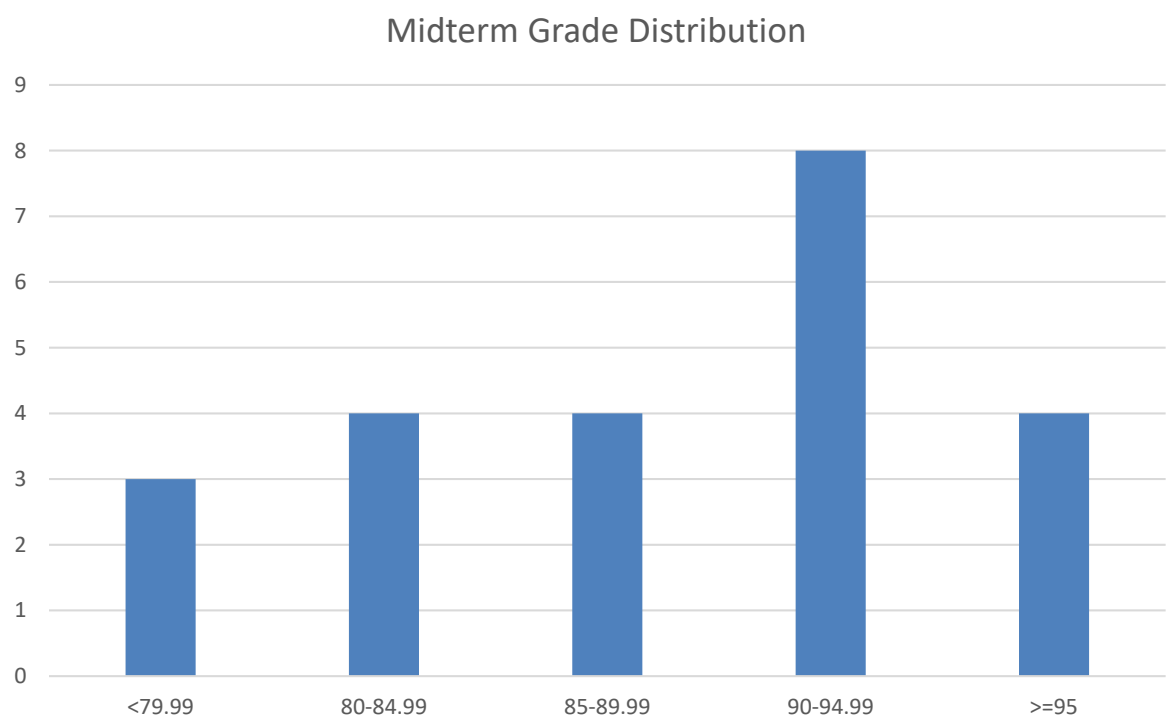
	Avg	Std Dev
1	1.07	0.59
2	2.00	0.00
3	1.52	0.51
4	4.87	0.63
5	5.00	0.00
6	4.80	0.65
7	4.22	1.57
8	3.65	1.64
9	4.96	0.21
10	4.48	0.99
11	4.87	0.34
12	8.00	2.07
Total	49.43	4.04
Grade	88.28	7.22



1. What do you think of the balance of theoretical vs. applied work?
2. What's been most useful to you (and why)?
3. What's been least useful (and why)?
4. What could students do to improve the class?
5. What could Matt do to improve the class?

Fine: 3
Reasonable: 1
Good: 8
Perfect: 1

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Online slides/lectures: 7
Theory/Kinematics: 2
Aligning labs/hw with lecture
Labs: 4

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Guest lecture / when Matt's gone: 3
Math: (3) Why not use built in software for kinematics caluclations?
HW 1
Using ROS
Intro to sensors
Locomotion
Piazza: rarely follow through

1. What do you think of the balance of theoretical vs. applied work?
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Piazza: 4
Review online lectures: 1
Come to lecture & Participate
Start earlier / work together more: 6

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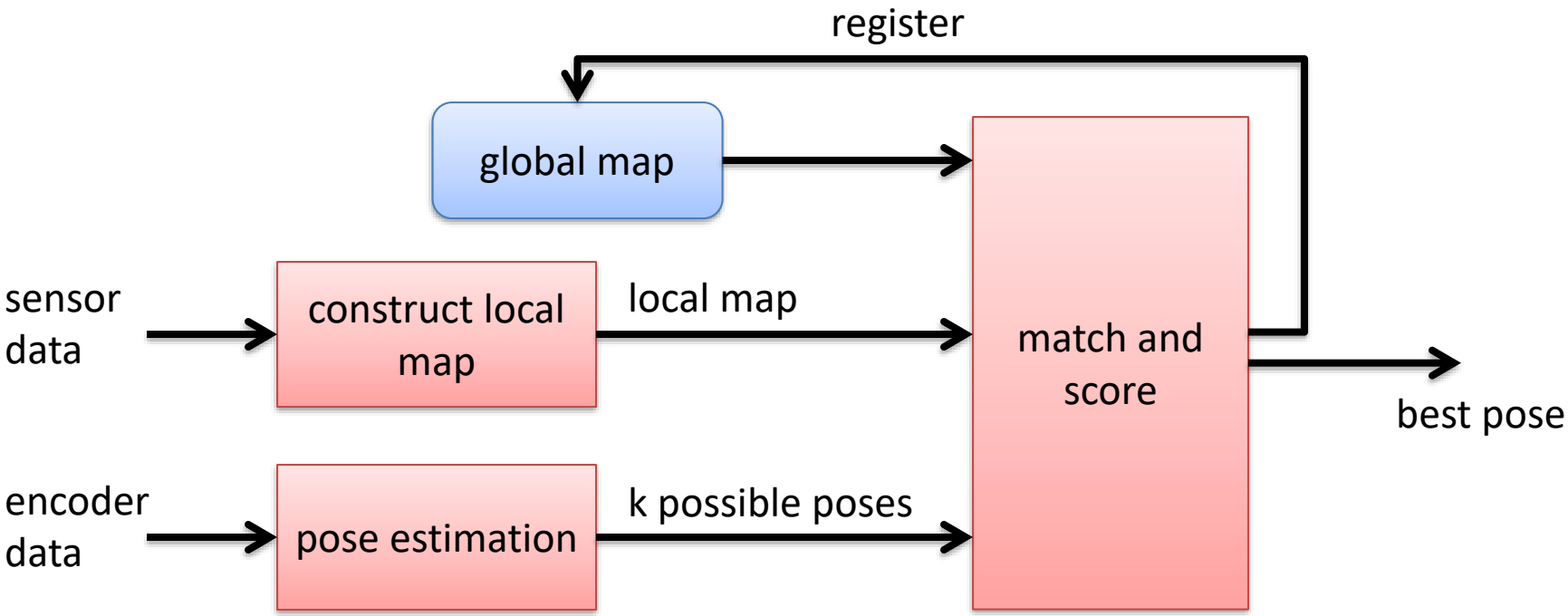
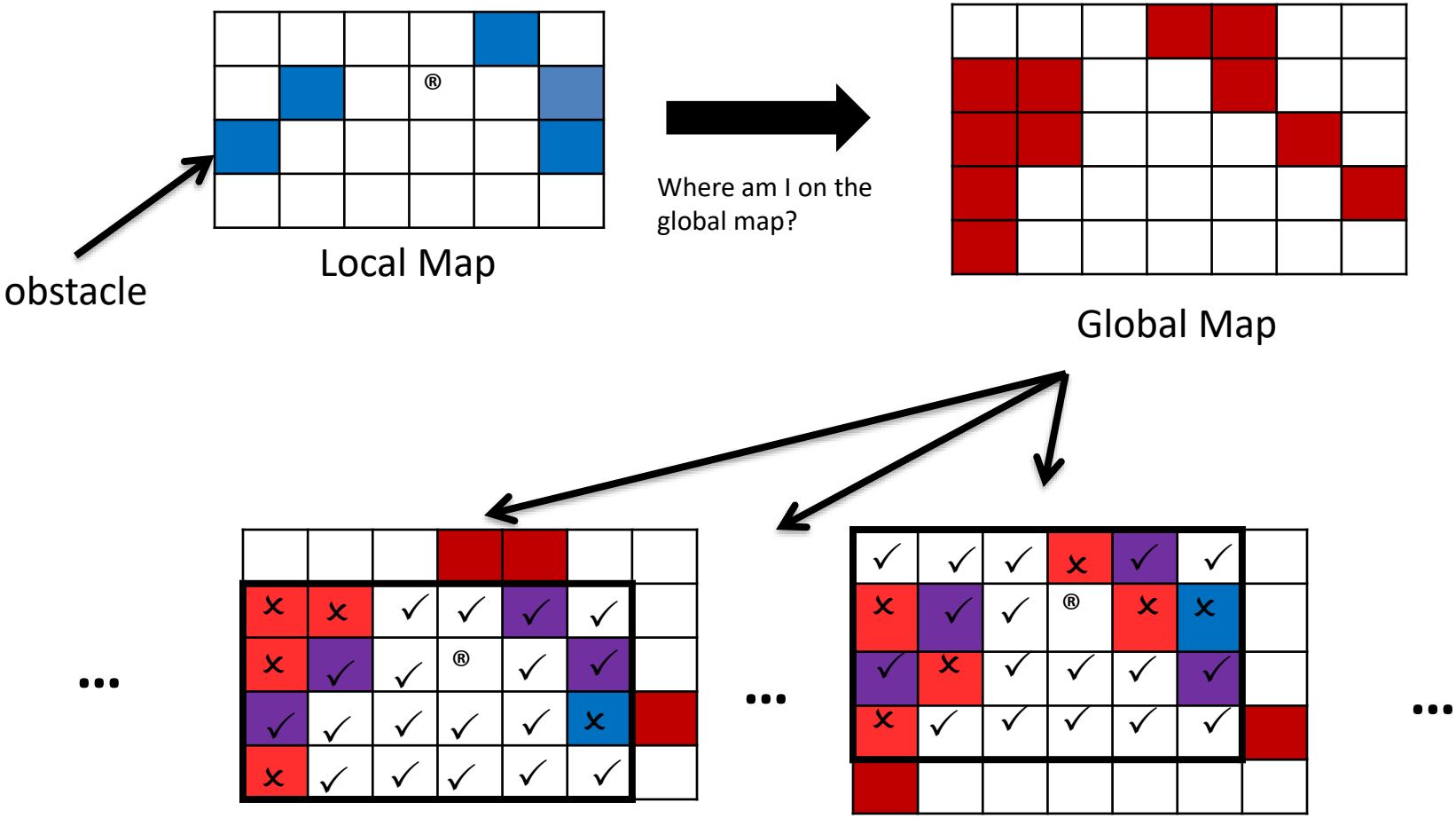
Faster grading: 1
More examples/demos:6
Keep starting labs in class: 2
More theory rather than ROS stuff
Baby us more through more stuff

Continuous Localization and Mapping

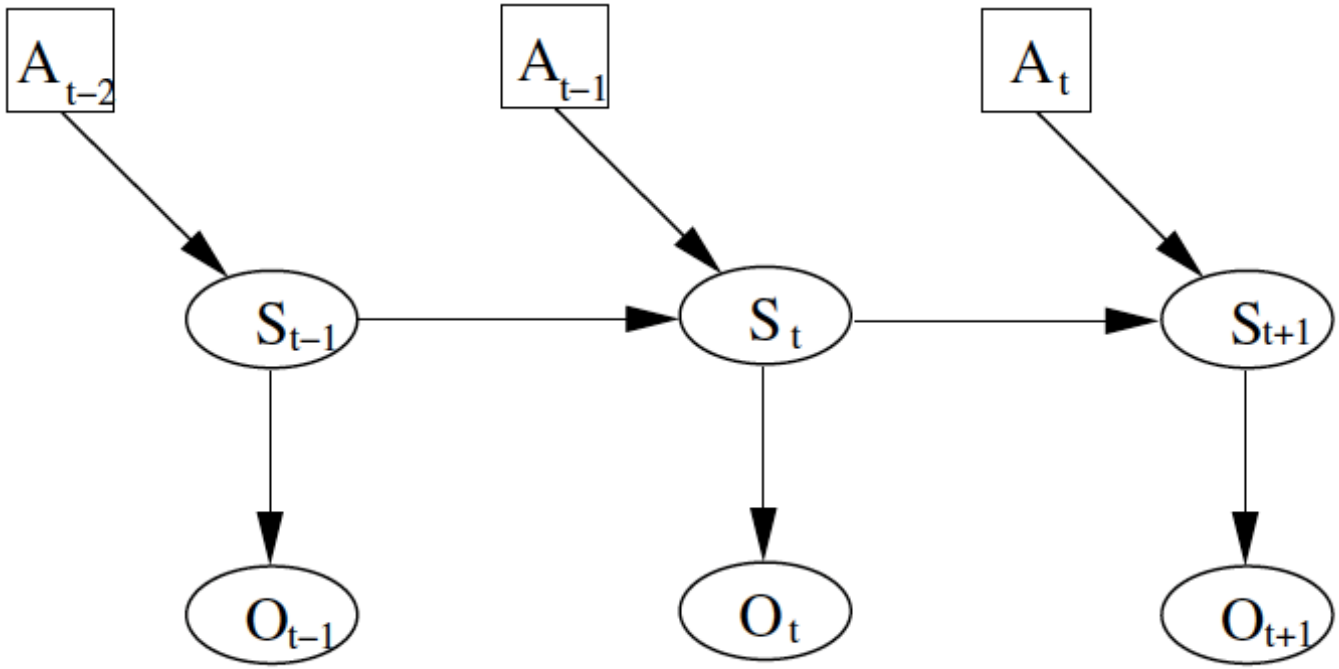


Matching



Examine different possible robot positions.

- General approach:



- A: action
- S: pose
- O: observation

Position at time t depends on position previous position and action, and current observation

- Pose at time *t* determines the observation at time *t*
- If we know the pose, we can say what the observation is

- But, this is *backwards*…
- Hello Bayes!

Quiz!

- If events a and b are independent,
  - p(a, b) =
- If events a and b are not independent,
  - p(a, b) =

- p(c|d) = ?

Mattel
1992

Quiz!

- If events a and b are independent,
  - $p(a, b) = p(a) \times p(b)$
- If events a and b are not independent,
  - $p(a, b) = p(a) \times p(b|a) = p(b) \times p(a|b)$

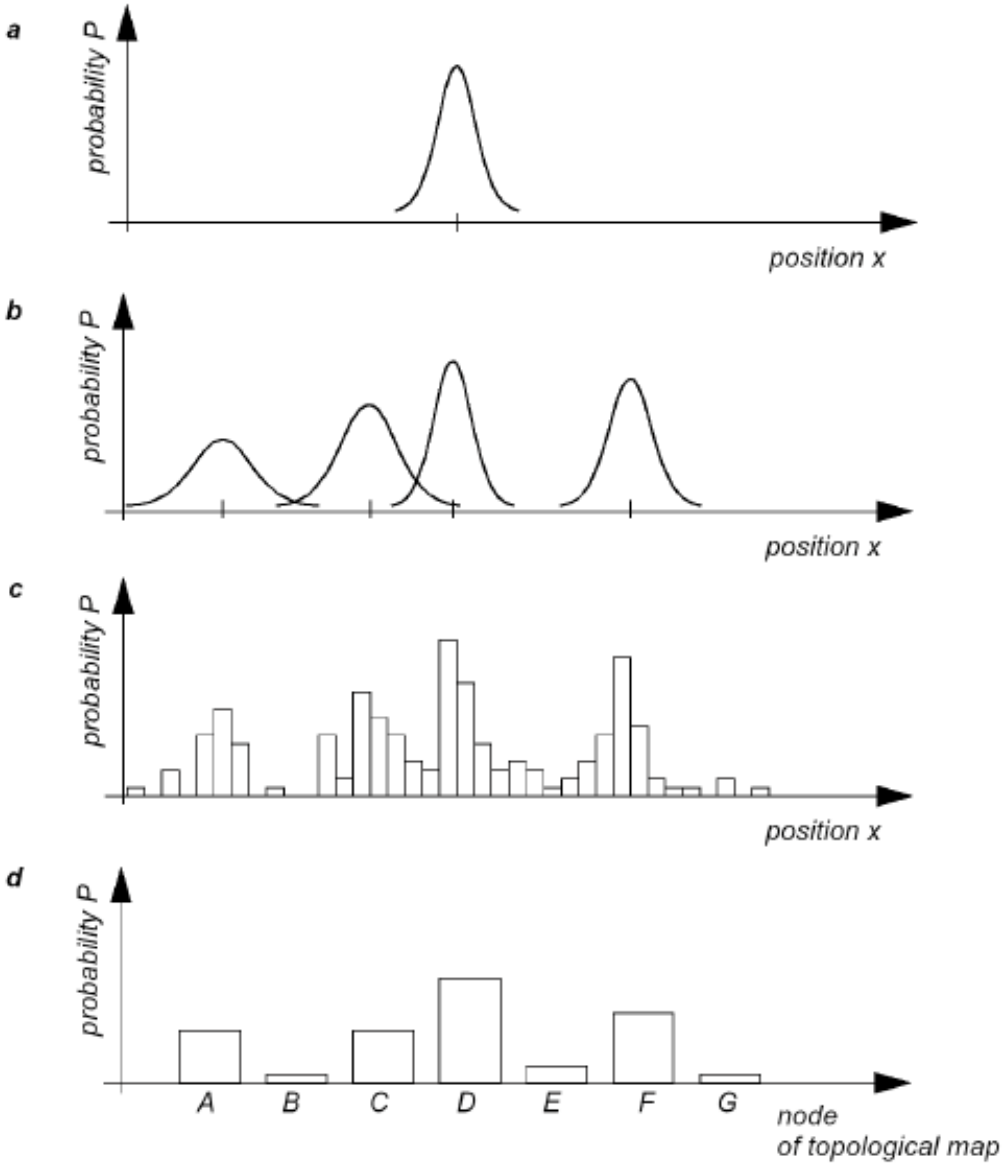
- $p(c|d) = p(c, d) / p(d) = p((d|c)\, p(c)) / p(d)$

Bayes Filtering

- Want to have a way of representing uncertainty
- Probability Distribution
  - Could be discrete or continuous
  - Prob. of each pose in set of all possible poses

- Belief
- Prior
- Posterior

Models of Belief



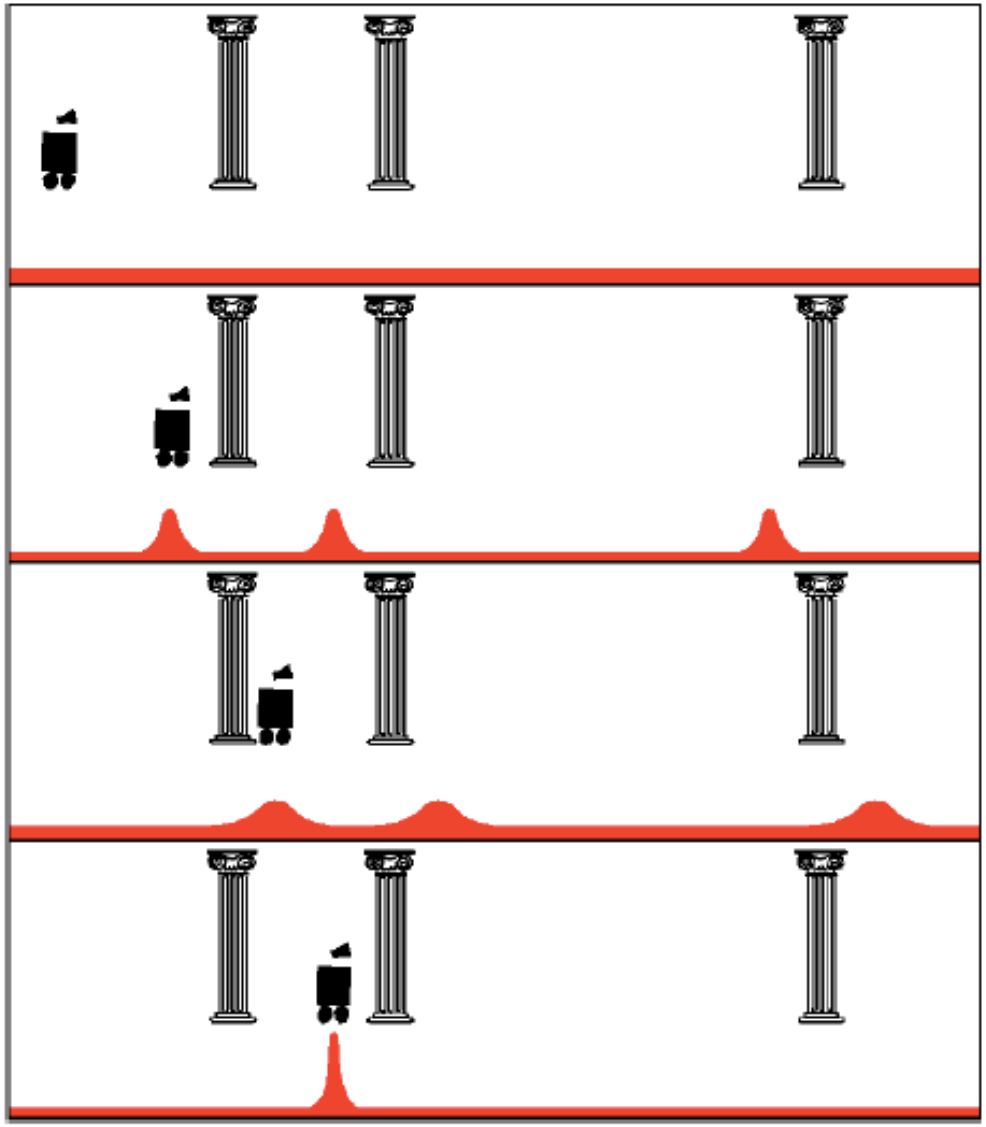
- Single hypothesis, continuous distribution
- Multiple hypothesis, continuous distribution
- Multiple hypothesis, discrete distribution
- Topological map, discrete distribution

1. Uniform Prior

2. Observation: see pillar

3. Action: move right

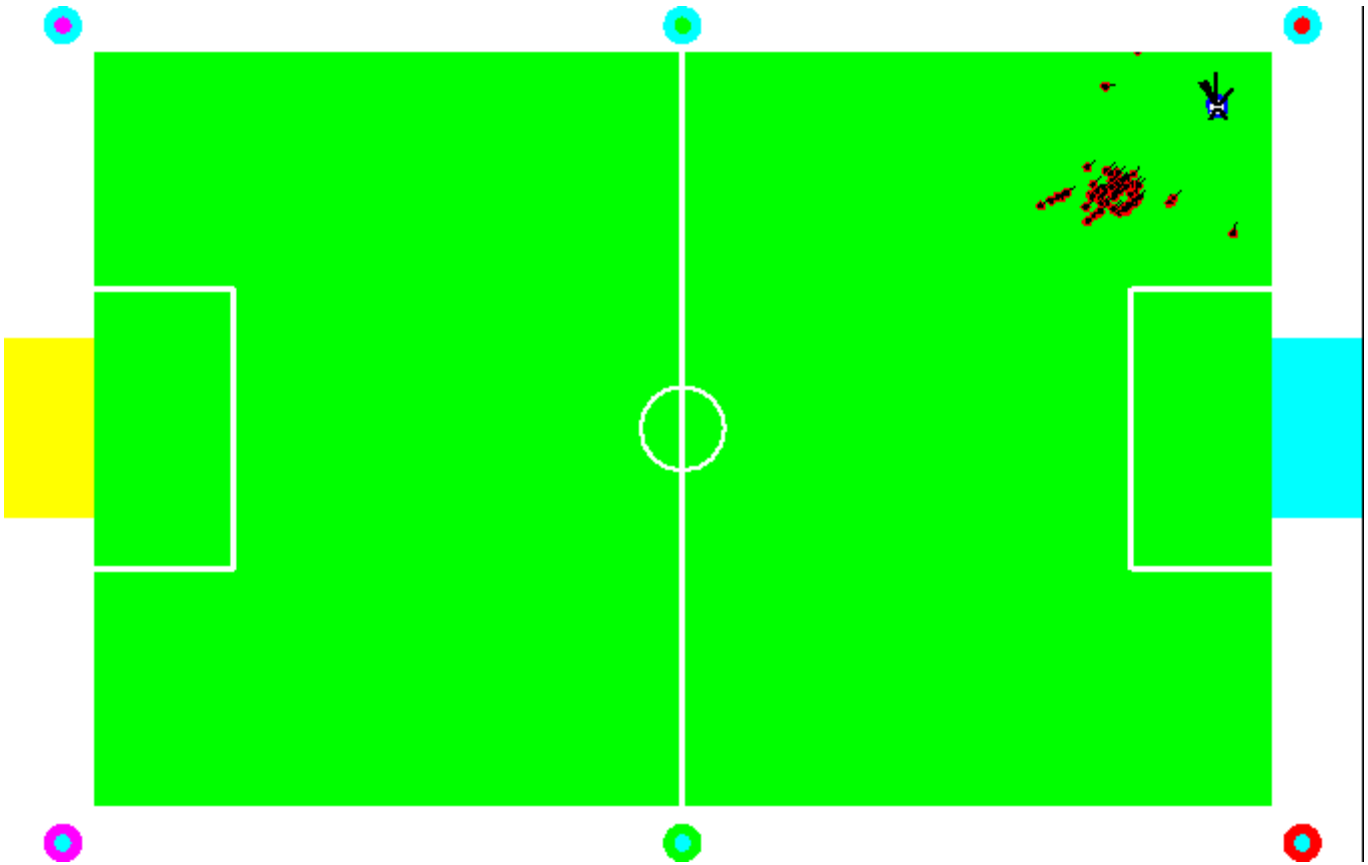
4. Observation: see pillar



Modeling objects in the environment

http://www.cs.washington.edu/research/rse-lab/projects/mcl

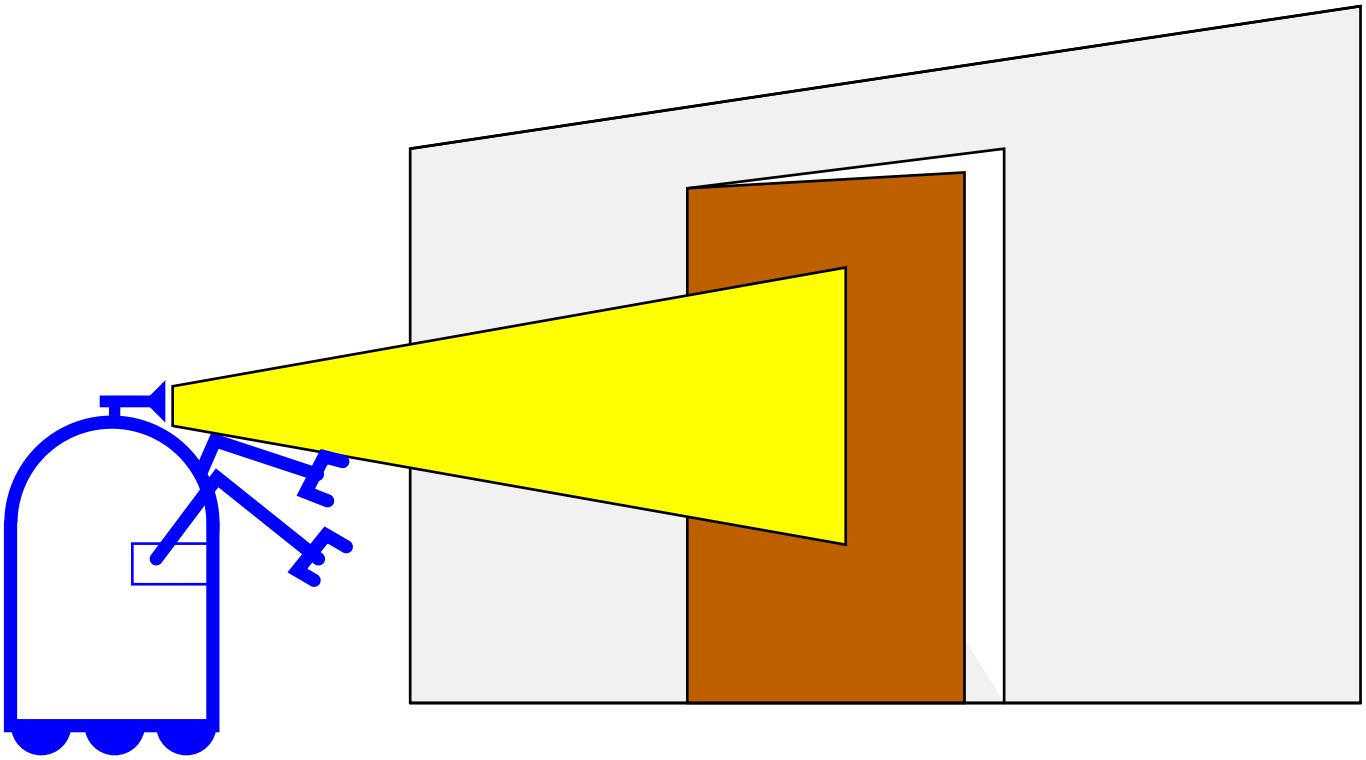
Modeling objects in the environment



http://www.cs.washington.edu/research/rse-lab/projects/mcl

Simple Example of State Estimation

- Suppose a robot obtains measurement z
- What is $P(open|z)$?



Causal vs. Diagnostic Reasoning

- $P(open|z)$ is diagnostic.
- $P(z|open)$ is causal.
- Often causal knowledge is easier to obtain.
- Bayes rule allows us to use causal knowledge:

Comes from sensor model.

$$P(open \mid z) = \frac{P(z \mid open)P(open)}{P(z)}$$

Bayes Formula

$$P(x, y) = P(x \mid y)P(y) = P(y \mid x)P(x)$$

$$\Rightarrow \quad \boxed{P(x \mid y) = \frac{P(y \mid x)\ P(x)}{P(y)} = \frac{\text{likelihood} \cdot \text{prior}}{\text{evidence}}}$$

If y is a new sensor reading:

$p(x)$ → Prior probability distribution

$p(x|y)$ → Posterior (conditional) probability distribution

$p(y|x)$ → Model of the characteristics of the sensor

$p(y)$ → Does not depend on x

Bayes Formula

$$P(x, y) = P(x \mid y)P(y) = P(y \mid x)P(x)$$

$$\Rightarrow \quad \boxed{P(x \mid y) = \frac{P(y \mid x)\ P(x)}{P(y)} = \frac{\text{likelihood} \cdot \text{prior}}{\text{evidence}}}$$

$$\Rightarrow \quad \boxed{P(x \mid y) = \frac{P(y \mid x)\ P(x)}{\sum_{x} P(y \mid x)P(x)}}$$

Example

- $P(z|open) = 0.6$ $\quad$ $P(z|\neg open) = 0.3$
- $P(open) = P(\neg open) = 0.5$

P(open | z) = ?

Example

$$P(open \mid z) = \frac{P(z \mid open)P(open)}{P(z)}$$

$$P(o \mid z) = \frac{P(z \mid o)\, P(o)}{\sum_x P(z \mid o)P(o)}$$

- $P(z|open) = 0.6$ $\quad$ $P(z|\neg open) = 0.3$
- $P(open) = P(\neg open) = 0.5$

$$P(open \mid z) = \frac{P(z \mid open)P(open)}{P(z \mid open)\, p(open) + P(z \mid \neg open)\, p(\neg open)}$$

$$P(open \mid z) = \frac{0.6 \cdot 0.5}{0.6 \cdot 0.5 + 0.3 \cdot 0.5} = \frac{2}{3} = 0.67$$

z raises the probability that the door is open.