Introduction to Mobile Robotics

Probabilistic Robotics

Wolfram Burgard

Probabilistic Robotics

Key idea:

Explicit representation of uncertainty
(using the calculus of probability theory)

- Perception = state estimation
- Action = utility optimization

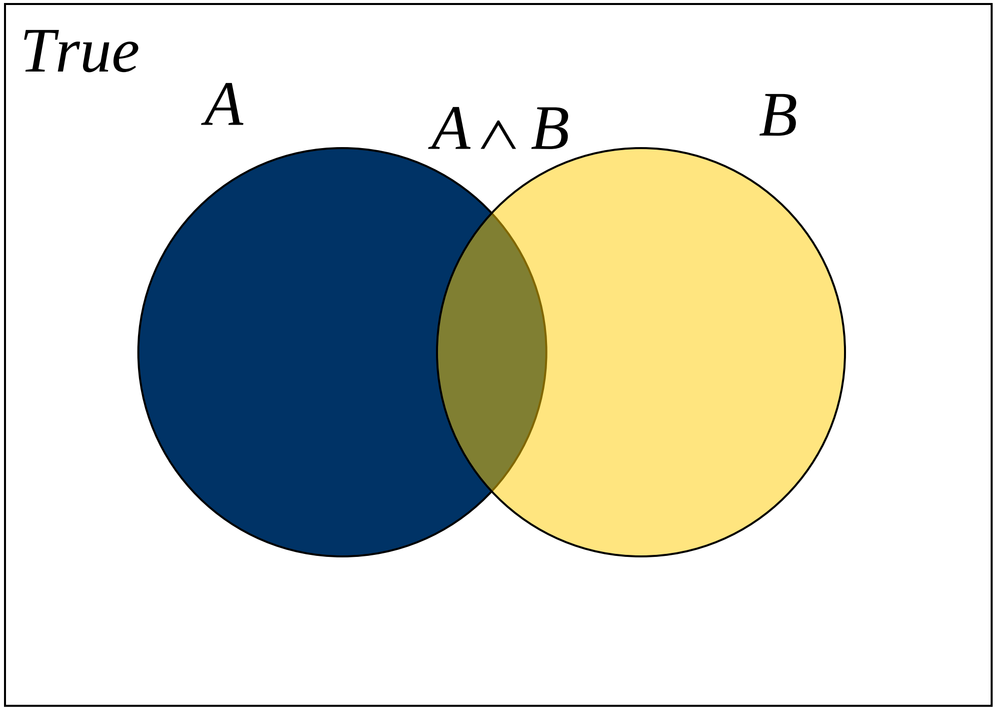
Axioms of Probability Theory

P*(A)* denotes probability that proposition *A* is true.

- $0 \leq \mathrm{P}(A) \leq 1$
- $\mathrm{P}(True) = 1 \qquad \mathrm{P}(False) = 0$
- $\mathrm{P}(A \vee B) = \mathrm{P}(A) + \mathrm{P}(B) - \mathrm{P}(A \wedge B)$

A Closer Look at Axiom 3

$$\mathrm{P}(A \vee B) = \mathrm{P}(A) + \mathrm{P}(B) - \mathrm{P}(A \wedge B)$$



Using the Axioms

$$\begin{aligned}
P(A \vee \neg A) &= P(A) + P(\neg A) - P(A \wedge \neg A) \\
P(True) &= P(A) + P(\neg A) - P(False) \\
1 &= P(A) + P(\neg A) - 0 \\
P(\neg A) &= 1 - P(A)
\end{aligned}$$

Discrete Random Variables

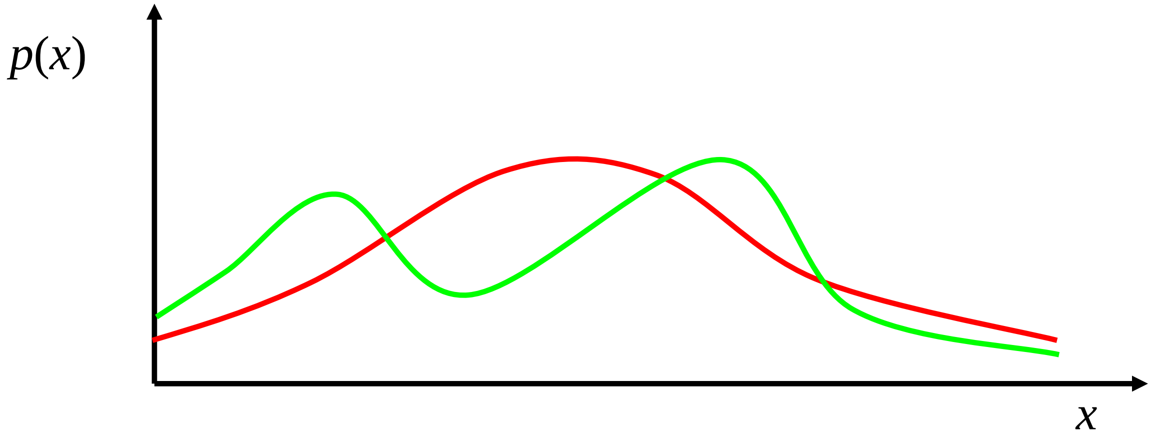
- X denotes a random variable
- X can take on a countable number of values in $\{x_1, x_2, \ldots, x_n\}$
- $P(X=x_i)$ or $P(x_i)$ is the probability that the random variable X takes on value x_i
- $P(\cdot)$ is called probability mass function
- E.g. $P(Room) = \langle 0.7, 0.2, 0.08, 0.02 \rangle$

Continuous Random Variables

- X takes on values in the continuum.
- $p(X=x)$ or $p(x)$ is a probability density function

$$P(x \in [a,b]) = \int_a^b p(x)\,dx$$

- E.g.



“Probability Sums up to One”

Discrete case

$$\sum_x P(x) = 1$$

Continuous case

$$\int p(x)\, dx = 1$$

Joint and Conditional Probability

- $P(X{=}x \text{ and } Y{=}y) = P(x,y)$

- If X and Y are independent then

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

- $P(x \mid y)$ is the probability of x given y

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

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

- If X and Y are independent then

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

Law of Total Probability

Discrete case

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

Continuous case

$$p(x) = \int p(x \mid y)\, p(y)\, dy$$

Marginalization

Discrete case

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

Continuous case

$$p(x) = \int p(x, y)\, dy$$

Bayes Formula

$$P(x,y) = P(x|y)P(y) = P(y|x)P(x)$$

$$\Rightarrow$$

$$\boxed{P(x|y) = \frac{P(y|x)\,P(x)}{P(y)} = \frac{\text{likelihood} \cdot \text{prior}}{\text{evidence}}}$$

Normalization

$$P(x \mid y) = \frac{P(y \mid x)\, P(x)}{P(y)} = \eta\, P(y \mid x) P(x)$$

$$\eta = P(y)^{-1} = \frac{1}{\sum_x P(y \mid x) P(x)}$$

Algorithm:

$$\forall x : \mathrm{aux}_{x|y} = P(y \mid x)\, P(x)$$

$$\eta = \frac{1}{\sum_x \mathrm{aux}_{x|y}}$$

$$\forall x : P(x \mid y) = \eta\, \mathrm{aux}_{x|y}$$

Bayes Rule with Background Knowledge

$$P(x \mid y, z) = \frac{P(y \mid x, z)\, P(x \mid z)}{P(y \mid z)}$$

Conditional Independence

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

- Equivalent to $P(x \mid z) = P(x \mid z, y)$

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

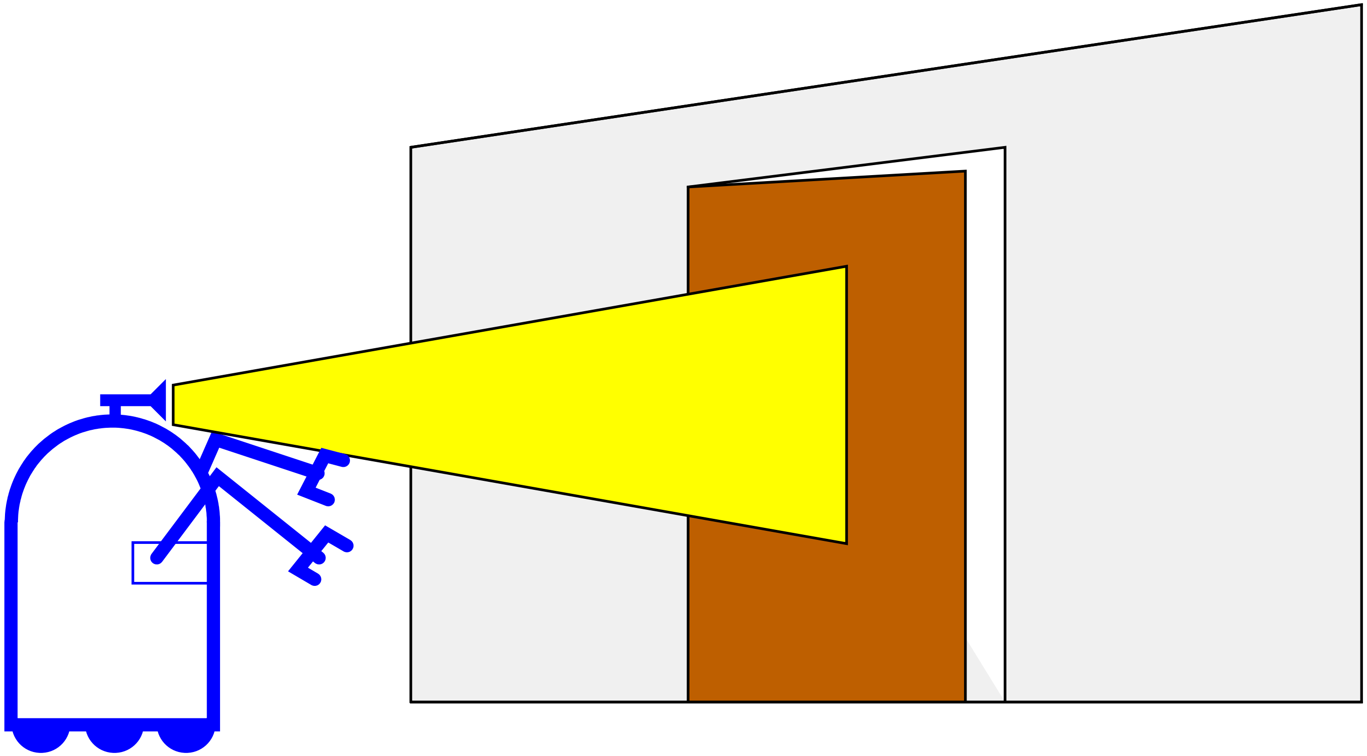
- But this does not necessarily mean

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

(independence/marginal independence)

Simple Example of State Estimation

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



Causal vs. Diagnostic Reasoning

- $P(open|z)$ is diagnostic
- $P(z|open)$ is causal
- In some situations, causal knowledge is easier to obtain **count frequencies!**
- Bayes rule allows us to use causal knowledge:

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

Example

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

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

$$P(open \mid z) = \frac{0.6 \cdot 0.5}{0.6 \cdot 0.5 + 0.3 \cdot 0.5} = \frac{0.3}{0.3 + 0.15} = 0.67$$

- *z* raises the probability that the door is open

Combining Evidence

- Suppose our robot obtains another observation z_2

- How can we integrate this new information?

- More generally, how can we estimate $P(x \mid z_1, \ldots, z_n)$?

Recursive Bayesian Updating

$$P(x \mid z_1, \ldots, z_n) = \frac{P(z_n \mid x, z_1, \ldots, z_{n-1})\, P(x \mid z_1, \ldots, z_{n-1})}{P(z_n \mid z_1, \ldots, z_{n-1})}$$

Markov assumption:

z_n is independent of $z_1,\ldots,z_{n-1}$ if we know x

$$P(x \mid z_1, \ldots, z_n) = \frac{P(z_n \mid x)\, P(x \mid z_1, \ldots, z_{n-1})}{P(z_n \mid z_1, \ldots, z_{n-1})}$$

$$= \eta\, P(z_n \mid x)\, P(x \mid z_1, \ldots, z_{n-1})$$

$$= \eta_{1\ldots n} \left[\prod_{i=1\ldots n} P(z_i \mid x) \right] P(x)$$

Example: Second Measurement

- $P(z_2|open) = 0.25$ $P(z_2|\neg open) = 0.3$
- $P(open|z_1)=2/3$

$$P(open \mid z_2, z_1) = \frac{P(z_2 \mid open)\, P(open \mid z_1)}{P(z_2 \mid open)\, P(open \mid z_1) + P(z_2 \mid \neg open)\, P(\neg open \mid z_1)}$$

$$= \frac{\frac{1}{4}\cdot\frac{2}{3}}{\frac{1}{4}\cdot\frac{2}{3} + \frac{3}{10}\cdot\frac{1}{3}} = \frac{\frac{1}{6}}{\frac{1}{6}+\frac{1}{10}} = \frac{\frac{1}{6}}{\frac{4}{15}} = \frac{5}{8} = 0.625$$

- z_2 lowers the probability that the door is open

Actions

- Often the world is **dynamic** since
  - **actions carried out by the robot**,
  - **actions carried out by other agents**,
  - or just the **time** passing by

  change the world

- How can we **incorporate** such **actions**?

Typical Actions

- The robot **turns its wheels** to move
- The robot **uses its manipulator** to grasp an object
- Plants grow over **time** ...

- Actions are **never carried out with absolute certainty**
- In contrast to measurements, **actions generally increase the uncertainty**

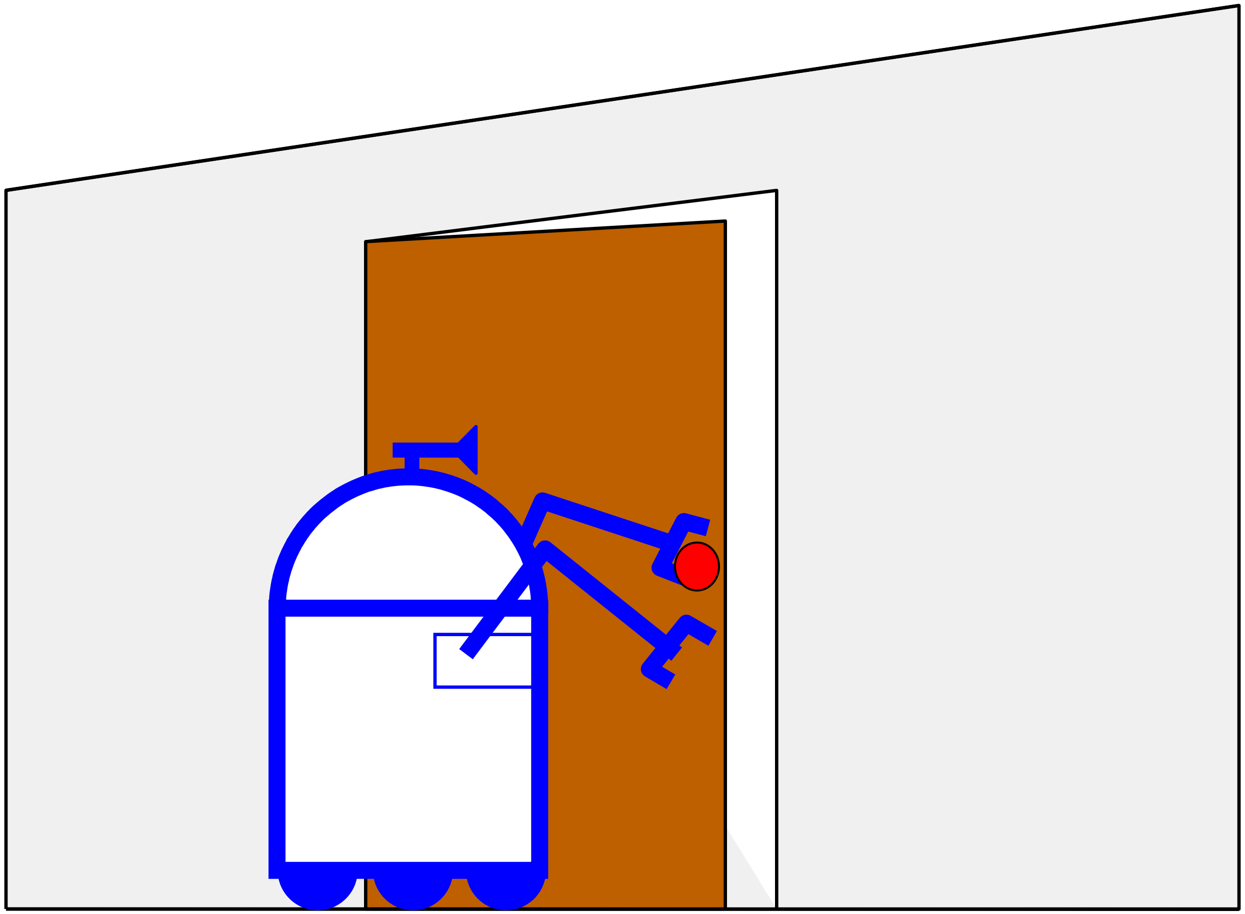
Modeling Actions

- To incorporate the outcome of an action *u* into the current "belief", we use the conditional pdf

$$P(x \mid u, x')$$

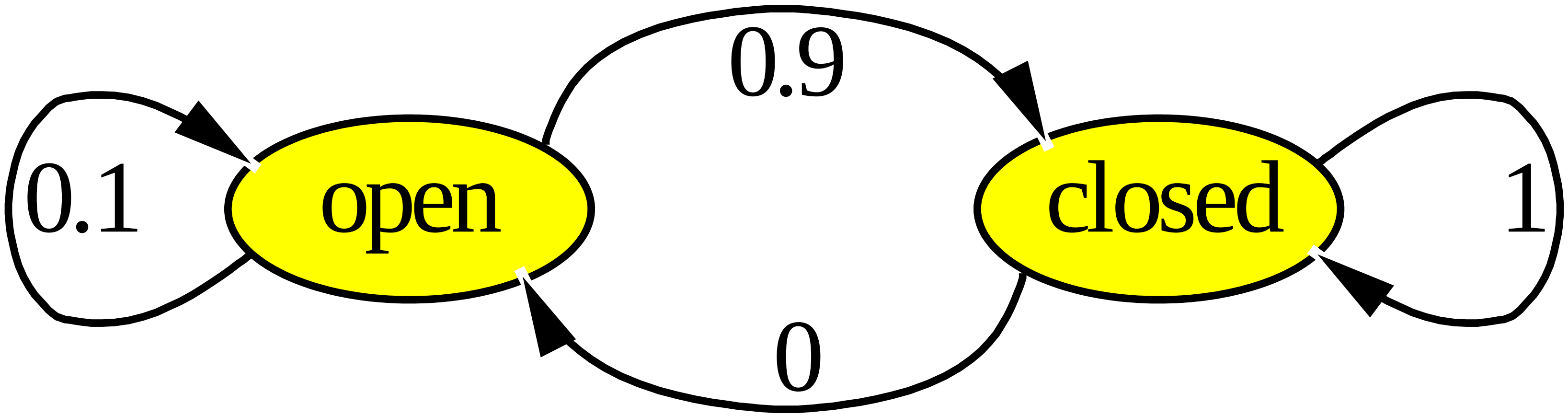
- This term specifies the pdf that **executing *u* changes the state from x' *to* x.**

Example: Closing the door



State Transitions

$P(x \mid u, x')$ for u = "close door":



If the door is open, the action "close door" succeeds in 90% of all cases

Integrating the Outcome of Actions

Continuous case:

$$P(x \mid u) = \int P(x \mid u, x')P(x' \mid \cancel{u})\,dx'$$

Discrete case:

$$P(x \mid u) = \sum P(x \mid u, x')P(x' \mid \cancel{u})$$

We will make an independence assumption to get rid of the u in the second factor in the sum.

Example: The Resulting Belief

$$P(closed \mid u) = \sum P(closed \mid u, x')P(x')$$

$$= P(closed \mid u, open)P(open)$$

$$+ P(closed \mid u, closed)P(closed)$$

$$= \frac{9}{10} * \frac{5}{8} + \frac{1}{1} * \frac{3}{8} = \frac{15}{16}$$

$$P(open \mid u) = \sum P(open \mid u, x')P(x')$$

$$= P(open \mid u, open)P(open)$$

$$+ P(open \mid u, closed)P(closed)$$

$$= \frac{1}{10} * \frac{5}{8} + \frac{0}{1} * \frac{3}{8} = \frac{1}{16}$$

$$= 1 - P(closed \mid u)$$

Bayes Filters: Framework

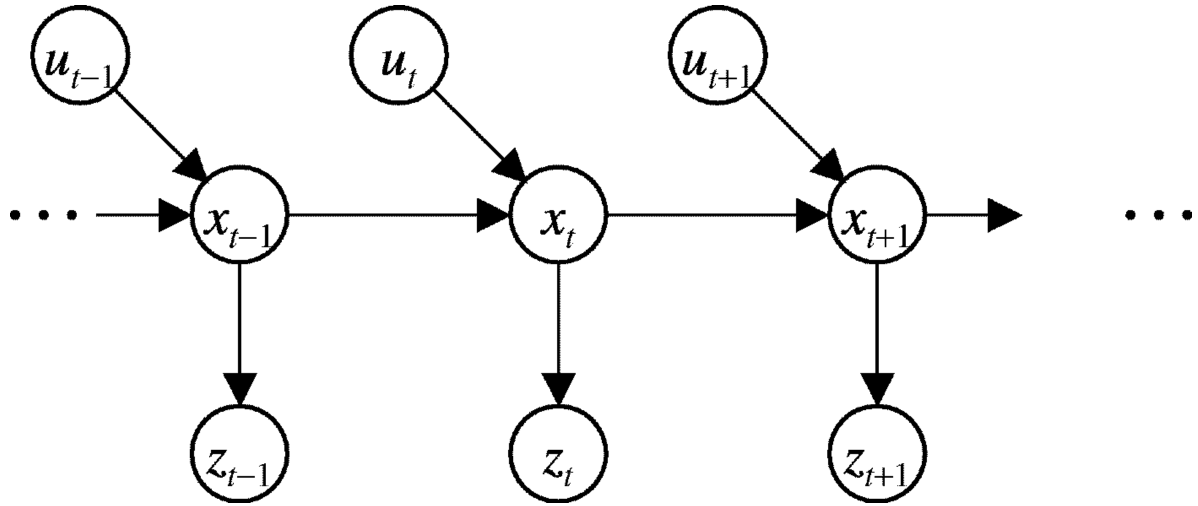
- **Given:**
  - Stream of observations *z* and action data *u:*

$$d_t = \{u_1, z_1, \ldots, u_t, z_t\}$$

  - Sensor model $P(z \mid x)$
  - Action model $P(x \mid u, x')$
  - Prior probability of the system state $P(x)$
- **Wanted:**
  - Estimate of the state X of a dynamical system
  - The posterior of the state is also called **Belief**:

$$Bel(x_t) = P(x_t \mid u_1, z_1, \ldots, u_t, z_t)$$

Markov Assumption



$$P(z_t \mid x_{0:t}, z_{1:t-1}, u_{1:t}) = P(z_t \mid x_t)$$

$$P(x_t \mid x_{1:t-1}, z_{1:t-1}, u_{1:t}) = P(x_t \mid x_{t-1}, u_t)$$

Underlying Assumptions

- Static world
- Independent noise
- Perfect model, no approximation errors

Bayes Filters

z = observation
u = action
x = state

$$\boxed{Bel(x_t)} = P(x_t \mid u_1, z_1 \ldots, u_t, z_t)$$

Bayes $$= \eta \, P(z_t \mid x_t, u_1, z_1, \ldots, u_t) \, P(x_t \mid u_1, z_1, \ldots, u_t)$$

Markov $$= \eta \, P(z_t \mid x_t) \, P(x_t \mid u_1, z_1, \ldots, u_t)$$

Total prob. $$= \eta \, P(z_t \mid x_t) \int P(x_t \mid u_1, z_1, \ldots, u_t, x_{t-1}) \, P(x_{t-1} \mid u_1, z_1, \ldots, u_t) \, dx_{t-1}$$

Markov $$= \eta \, P(z_t \mid x_t) \int P(x_t \mid u_t, x_{t-1}) \, P(x_{t-1} \mid u_1, z_1, \ldots, u_t) \, dx_{t-1}$$

Markov $$= \eta P(z_t \mid x_t) \int P(x_t \mid u_t, x_{t-1}) P(x_{t-1} \mid u_1, z_1, \ldots, z_{t-1}) \, dx_{t-1}$$

$$\boxed{= \eta P(z_t \mid x_t) \int P(x_t \mid u_t, x_{t-1}) \, Bel(x_{t-1}) \, dx_{t-1}}$$

$$Bel(x_t) = \eta P(z_t \mid x_t) \int P(x_t \mid u_t, x_{t-1}) Bel(x_{t-1}) dx_{t-1}$$

Algorithm **Bayes_filter**(*Bel(x), d*):

η=0

If *d* is a perceptual data item *z* then

  For all *x* do

    $Bel'(x) = P(z \mid x) Bel(x)$

    $\eta = \eta + Bel'(x)$

  For all *x* do

    $Bel'(x) = \eta^{-1} Bel'(x)$

Else if *d* is an action data item *u* then

  For all *x* do

    $Bel'(x) = \int P(x \mid u, x') \, Bel(x') \, dx'$

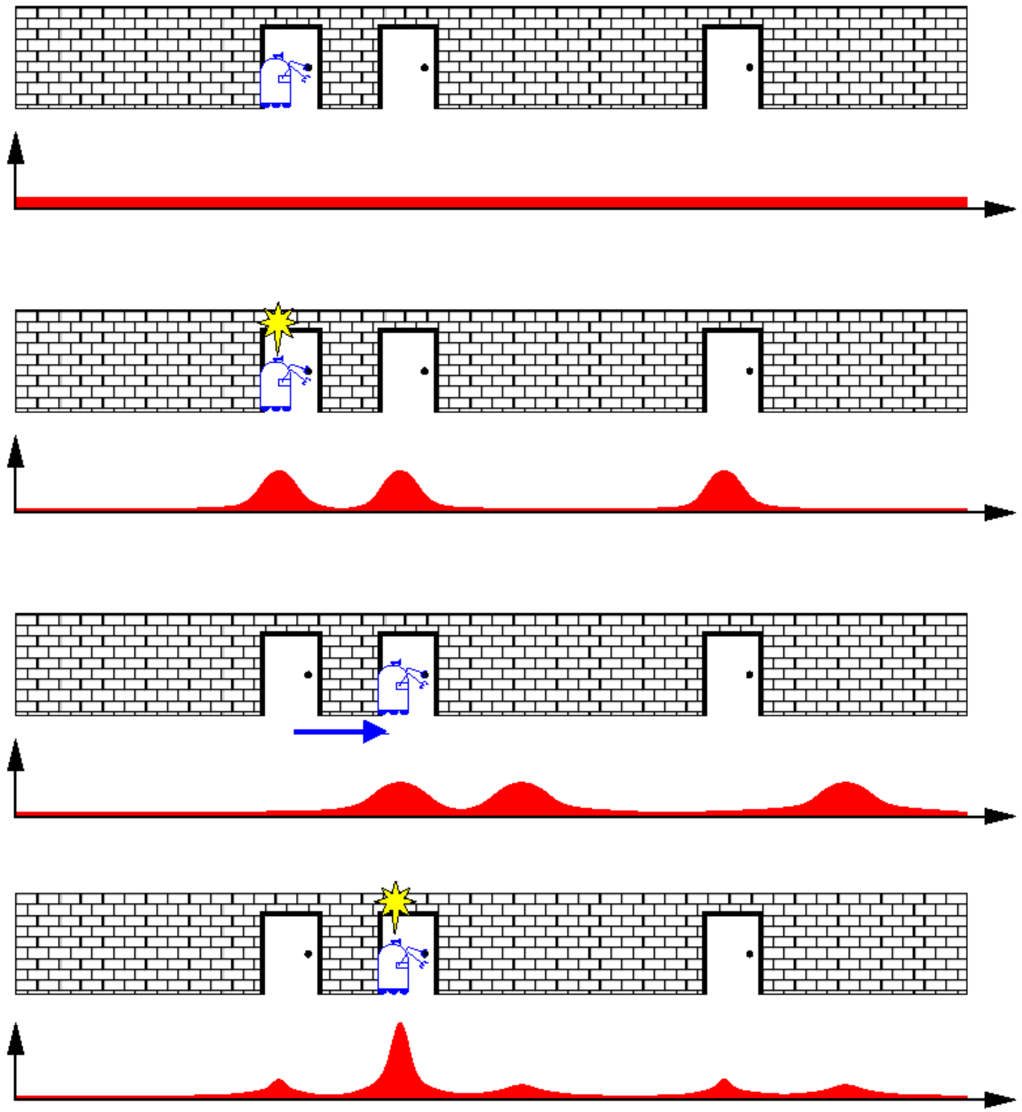
Return *Bel'(x)*

Bayes Filters are Familiar!

$$Bel(x_t) = \eta P(z_t \mid x_t) \int P(x_t \mid u_t, x_{t-1}) Bel(x_{t-1}) dx_{t-1}$$

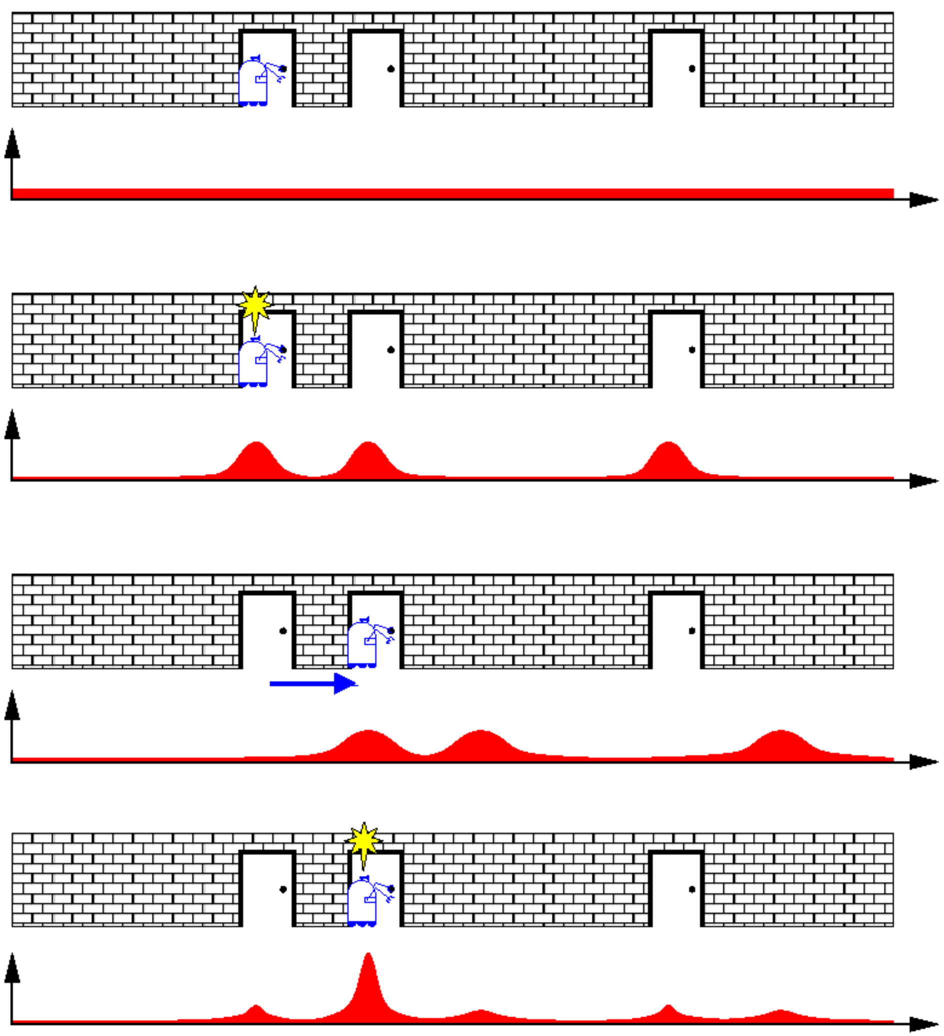
- Kalman filters
- Particle filters
- Hidden Markov models
- Dynamic Bayesian networks
- Partially Observable Markov Decision Processes (POMDPs)

Probabilistic Localization



Probabilistic Localization

$$Bel(x \mid z, u) \;=\; \alpha\, p(z \mid x) \int_{x'} p(x \mid u, x')\; Bel(x')\, dx'$$



Summary

- Bayes rule allows us to compute probabilities that are hard to assess otherwise.
- Under the Markov assumption, recursive Bayesian updating can be used to efficiently combine evidence.
- Bayes filters are a probabilistic tool for estimating the state of dynamic systems.