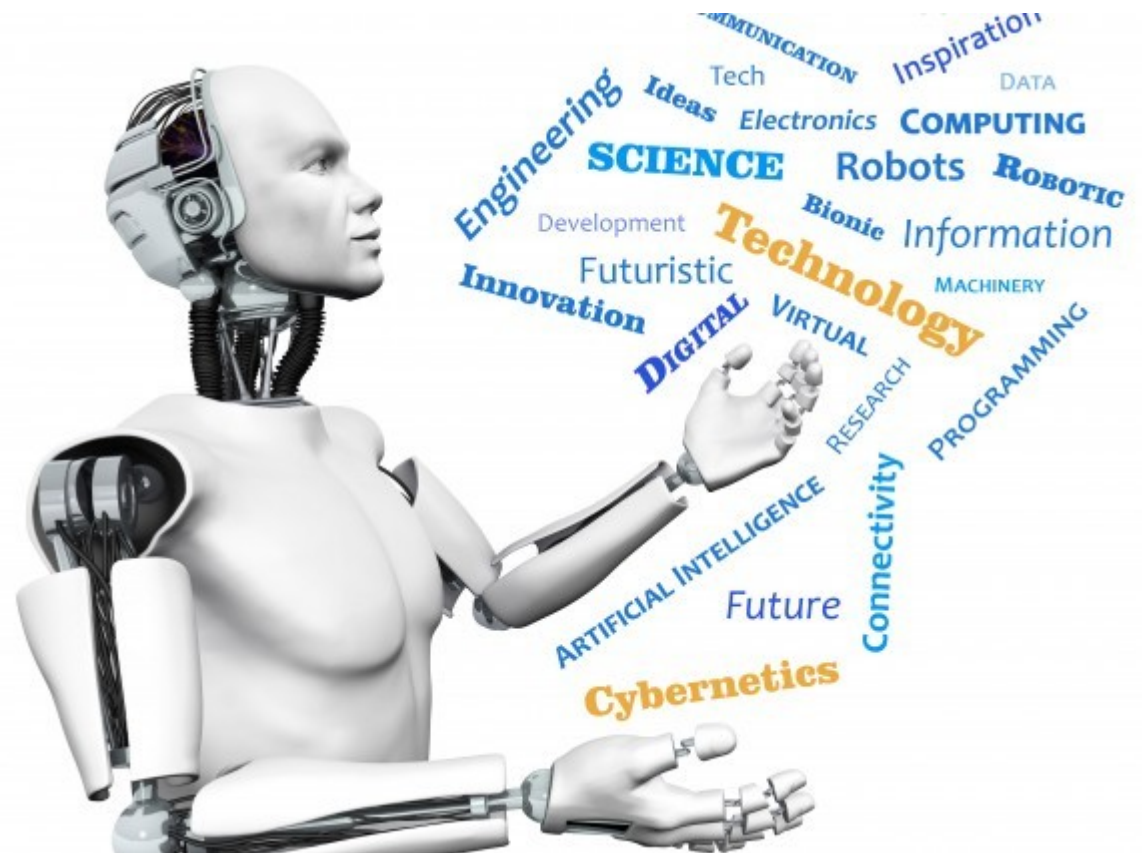


15-494/694: Cognitive Robotics

Dave Touretzky

Lecture 5:

Particle Filters and
Localization

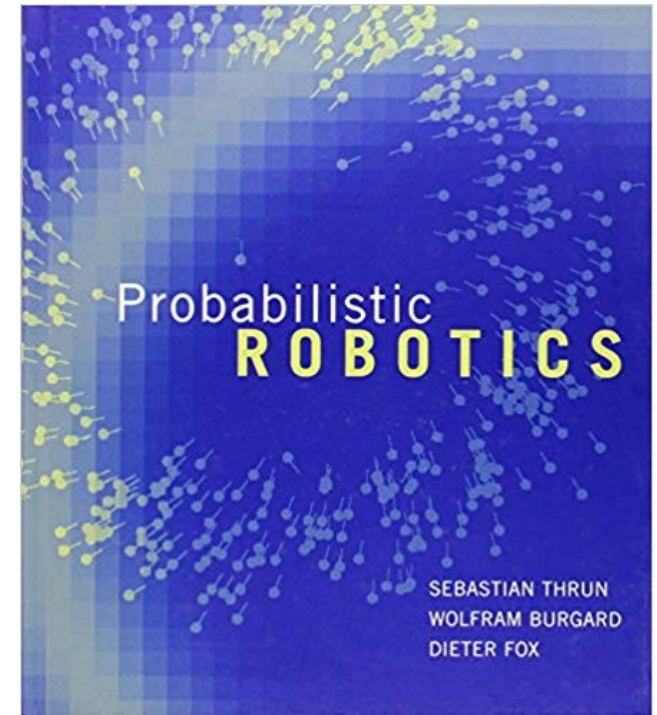


Outline

- Probabilistic Robotics
- Belief States
- Parametric and non-parametric representations
- Motion model
- Sensor model
- Evaluation and resampling
- Demos

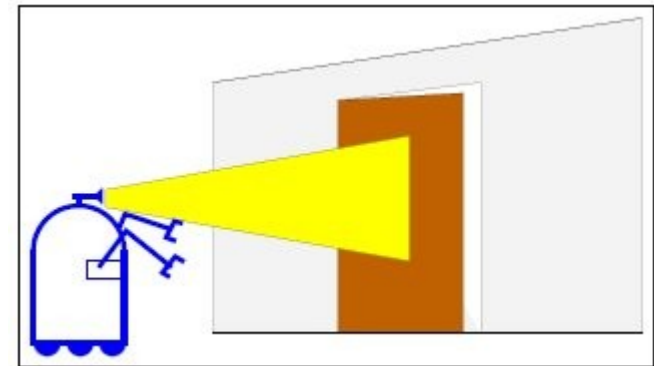
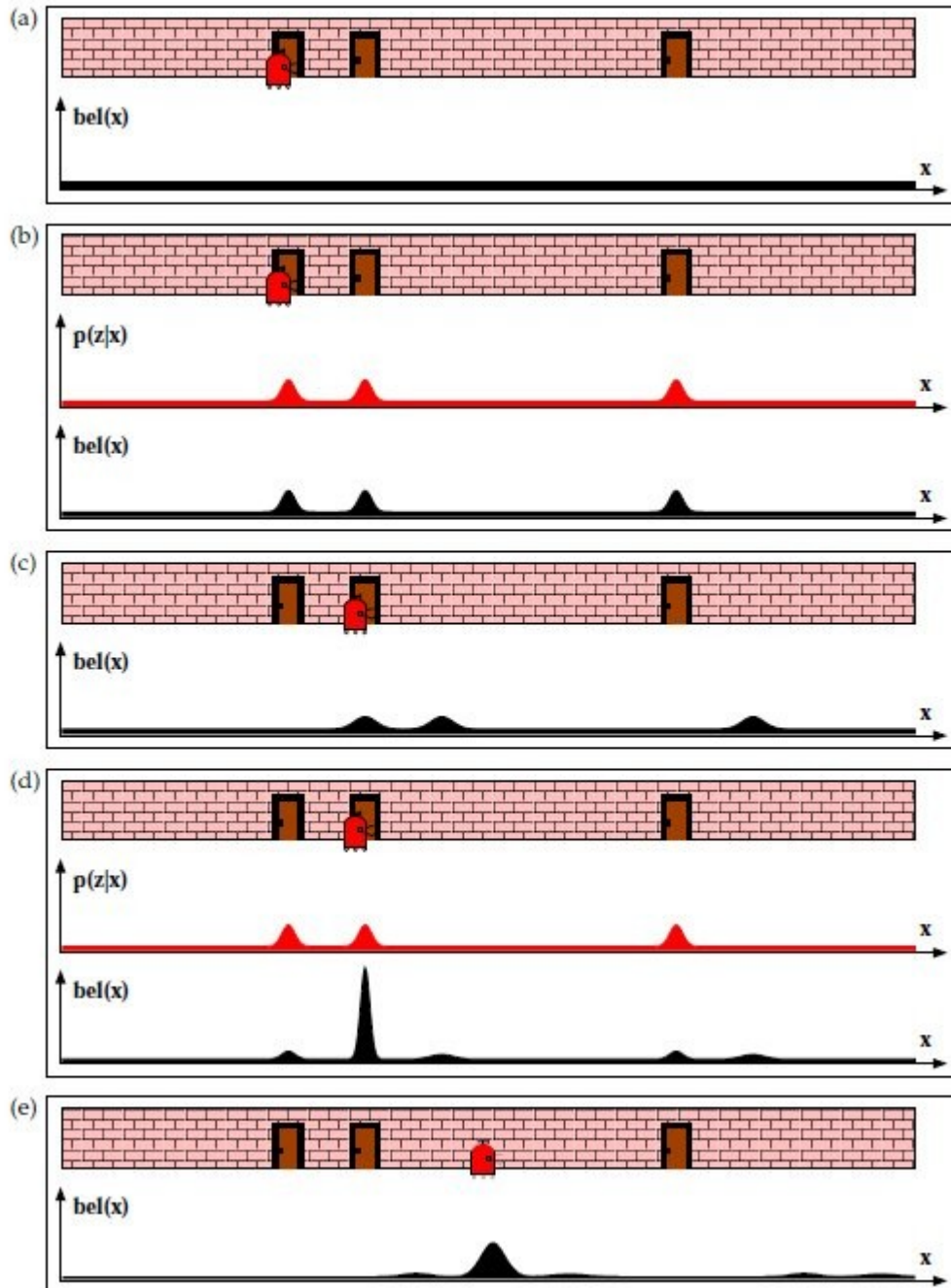
Probabilistic Robotics

- The world is uncertain:
 - Sensors are noisy and inaccurate.
 - Actuators are unreliable.
 - Other actors can affect the world.
- Embrace the uncertainty!
- How?
 - Explicitly *model* our uncertainty about sensors and actions.
 - Replace discrete states with beliefs: *probability distributions* over states.
 - Use Bayesian filtering to update our beliefs.



Beliefs

are probability distributions



Figures from Thrun, Burgard, and Fox (2005)
Probabilistic Robotics

Some Notation

- x_t = state at time t
- u_t = *control signal at time t*
- z_t = *sensor input at time t*
- We don't know x_t with certainty; we have *a priori* (before measurement) beliefs about it:

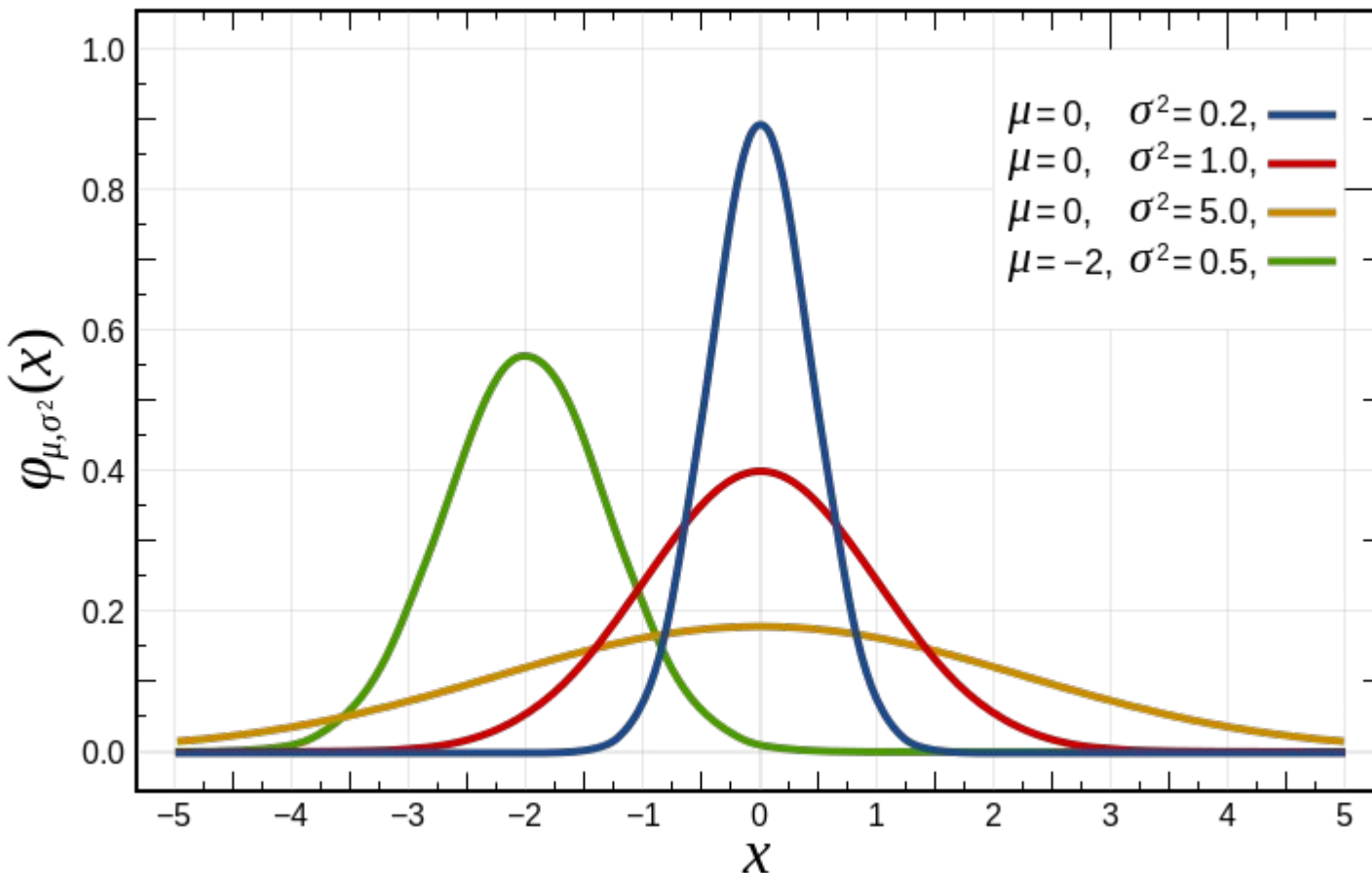
$$\overline{\text{bel}}(x_t) = p(x_t \mid z_{1:t-1}, u_{1:t})$$

- New sensor data z_t updates our belief:

$$\text{bel}(x_t) = \eta p(z_t \mid x_t) \cdot \overline{\text{bel}}(x_t)$$

Parametric Representations (1)

- Represent a probability distribution using an analytic function described by a small number of parameters.
- Most common example: Gaussian

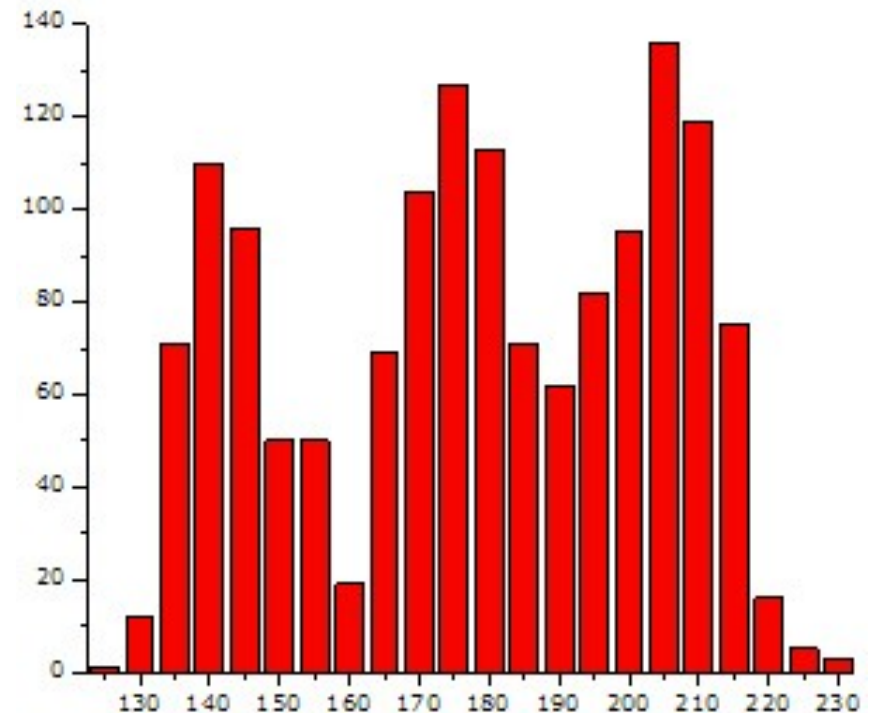


Parametric Representations (2)

- Good points:
 - Compact representation: just a few numbers
 - For a Gaussian: mean μ and variance σ^2
 - Fast to compute
 - Nice mathematical properties
 - **Easy to sample from**
- Drawbacks:
 - May not match the data very well
 - Can give bad results if the fit is poor

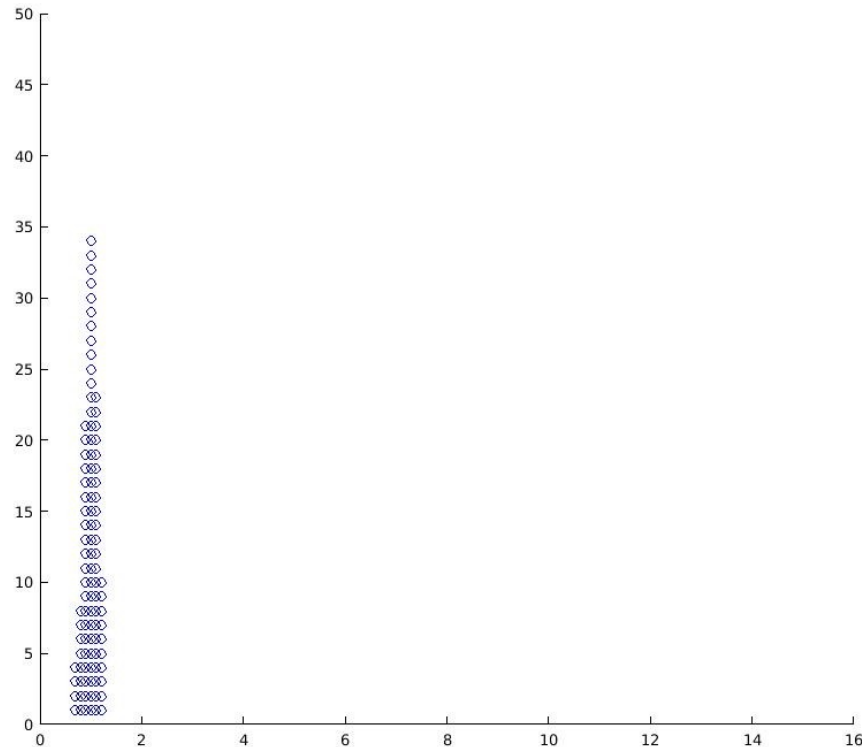
Nonparametric Representations

- No preconceived formula for the distribution.
- Instead, maintain a representation of the actual distribution, via *sampling*.
- Example: histogram
- Good points:
 - Can represent completely arbitrary distributions
- Drawbacks:
 - Requires more storage
 - Expensive to update



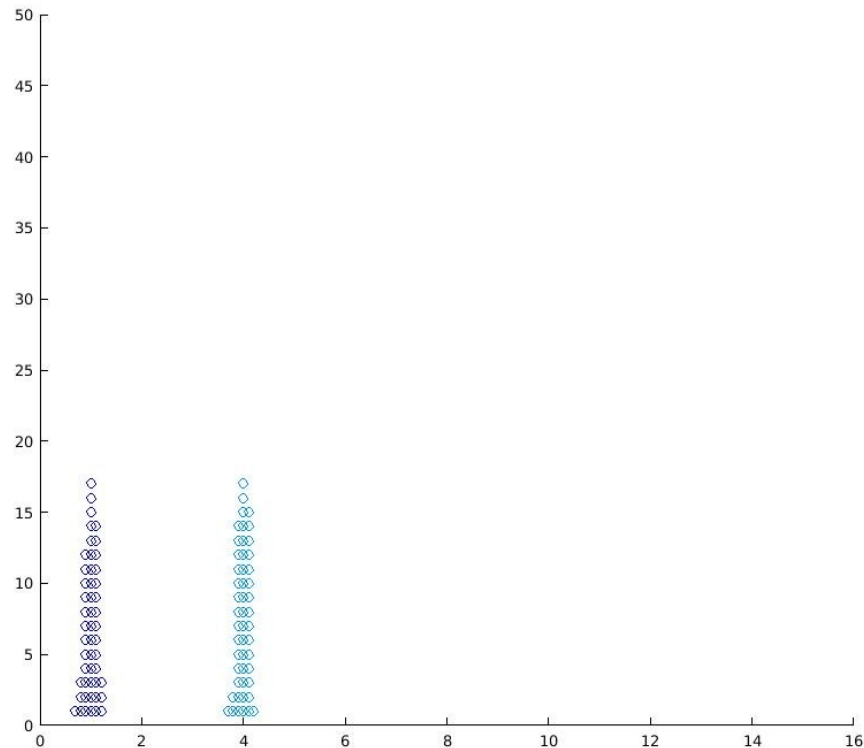
Where Is The Robot?

- Parametric: the robot is at $x=1$ with $\sigma^2 = 0.2$
- Non-parametric: 100 samples indicating robot position.



Where Is The Robot?

- Parametric: fail (or put robot at the mean: $x=2.5$)
- Non-parametric: 100 samples.



Particle Filters

- A particle filter is an efficient non-parametric representation of a distribution.
- Each particle represents a sample drawn from the distribution.
- As the distribution changes, we update the particles.
- Three kinds of updating:
 - Change the *value* the particle encodes (motion model).
 - Change the *weight* assigned to the particle (sensor model).
 - *Resample* the distribution, getting a fresh set of particles with initially equal weights.

Bayesian Filter, part 1

- Our belief about the robot's position at time $t-1$ is a probability distribution $p(x_{t-1})$, which we represent as a set of *samples*.
- At time t the robot moves, following some control signal u_t , producing a new distribution $p(x_t)$.
- A *motion model* defines how our new prediction $\overline{bel}(x_t)$ arises from applying u_t .

$$\overline{bel}(x_t) = \int p(x_t | x_{t-1}, u_t) \cdot bel(x_{t-1}) \, dx_{t-1}$$

Why Are We Integrating?

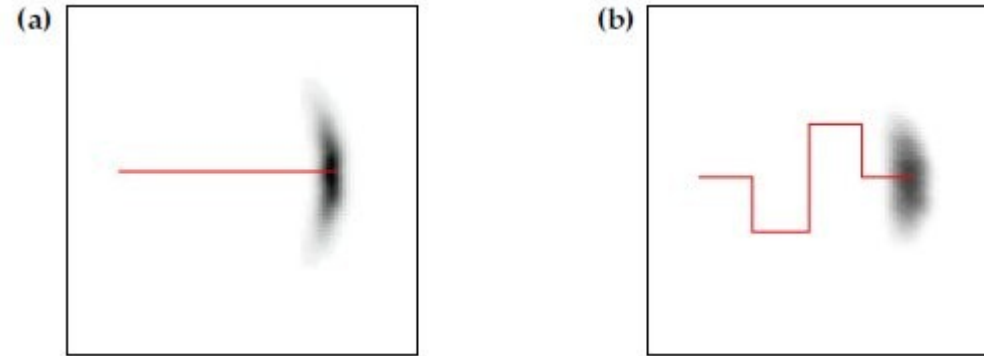
$$\overline{bel}(x_t) = \int \underbrace{p(x_t | x_{t-1}, u_t)}_{\substack{\text{Probability of} \\ \text{arriving at } x_t \text{ given} \\ \text{that we were} \\ \text{previously at } x_{t-1} \\ \text{and got control} \\ \text{signal } u_t.}} \cdot \underbrace{bel(x_{t-1})}_{\substack{\text{Belief that we} \\ \text{were previously} \\ \text{at location } x_{t-1}}} \underbrace{dx_{t-1}}_{\substack{\text{All} \\ \text{possible} \\ \text{previous} \\ \text{locations} \\ x_{t-1}}}$$

Integrated over all possible starting locations x_{t-1} .

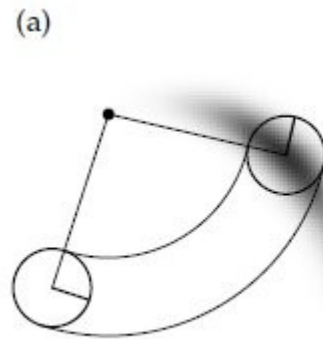
Motion Models

- Motion models express the noisiness of motion u_t .
- Typically use a simple parametric distribution.
 - Easy to sample.
- We represented the distribution $p(x_{t-1})$ as a set of a *posteriori* samples $\text{bel}(x_{t-1})$. Motion gives us $\overline{\text{bel}}(x_t)$.
- How do we sample $\overline{\text{bel}}(x_t)$?
- Solution: for each sample in $\text{bel}(x_{t-1})$, draw a value from the motion model's distribution and add it to the sample value.

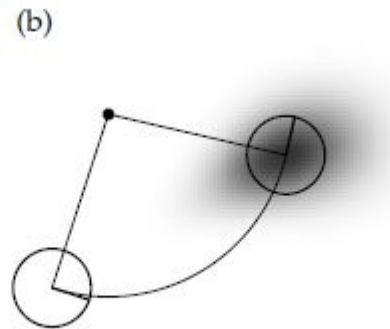
Motion Model $p(x_t | x_{t-1}, u_t)$



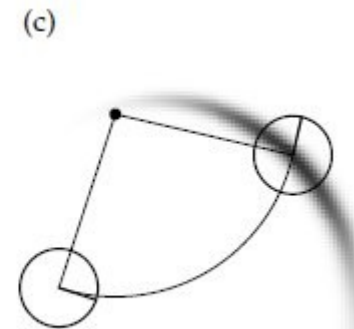
Figures from Thrun, Burgard, and Fox (2005) *Probabilistic Robotics*



Moderate
Noise Values

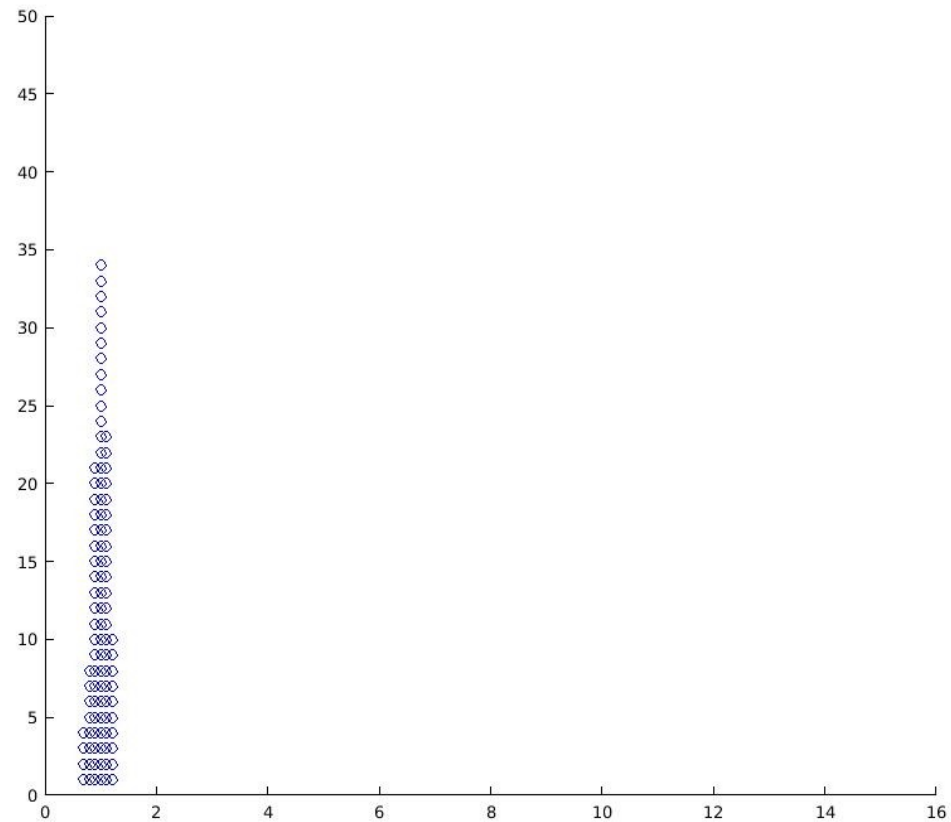


High
Translational
Uncertainty

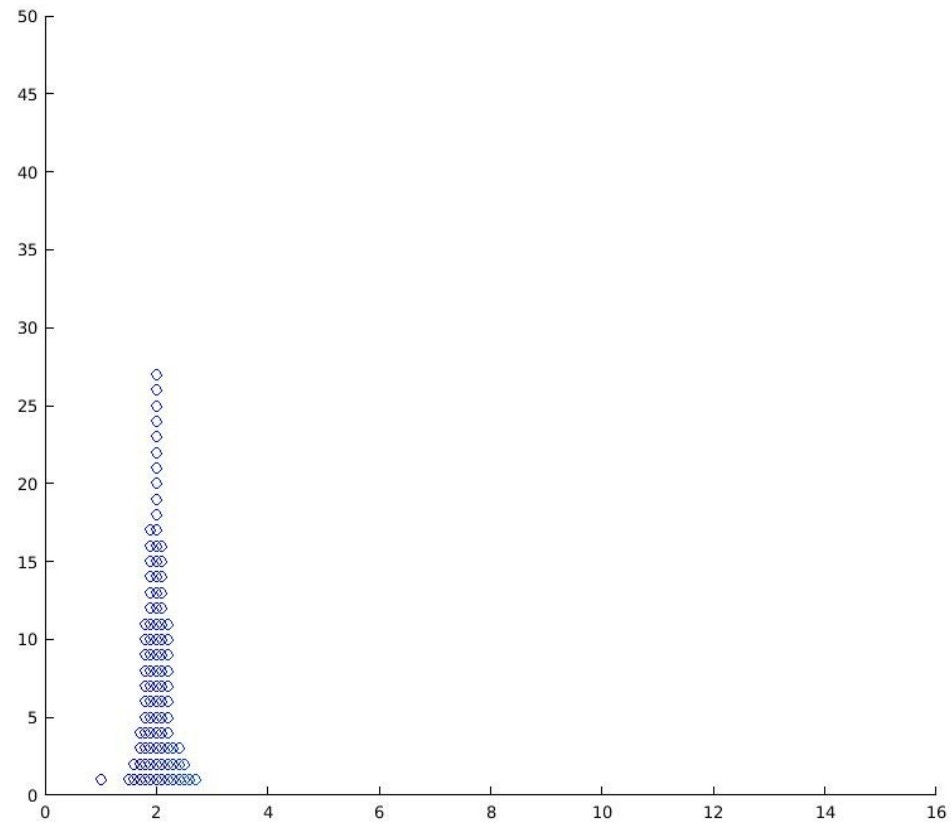


High
Rotational
Uncertainty

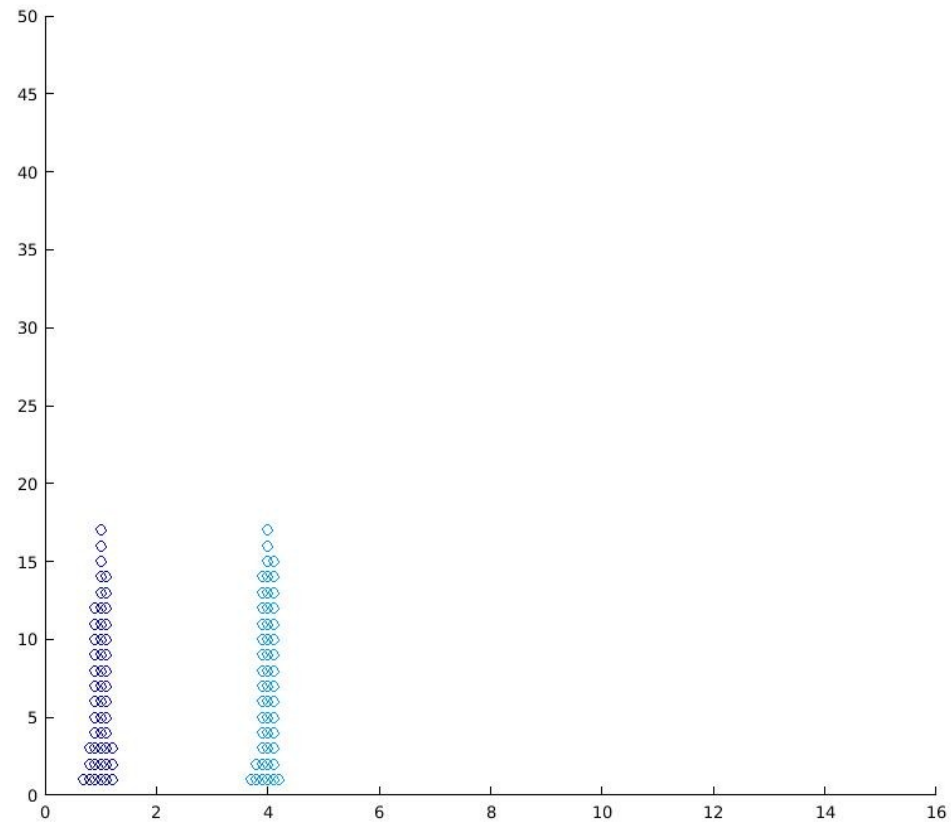
Robot at $t=0$: $\text{bel}(x_0)$



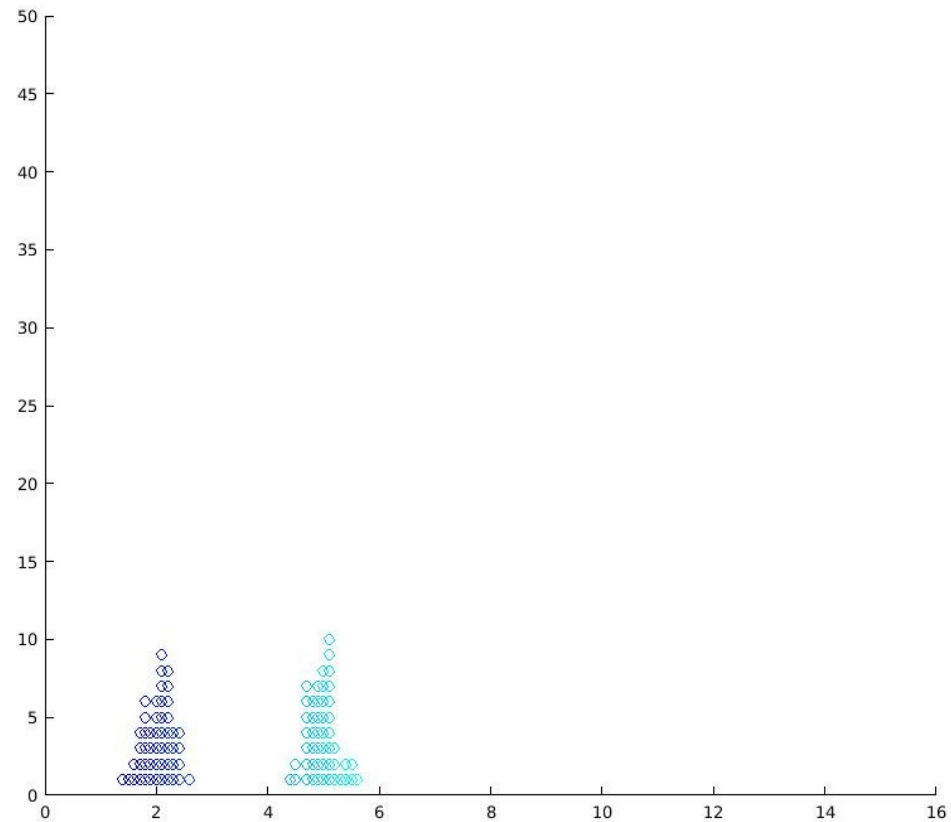
Prediction at $t=1$: $\overline{\text{bel}}(x_1)$



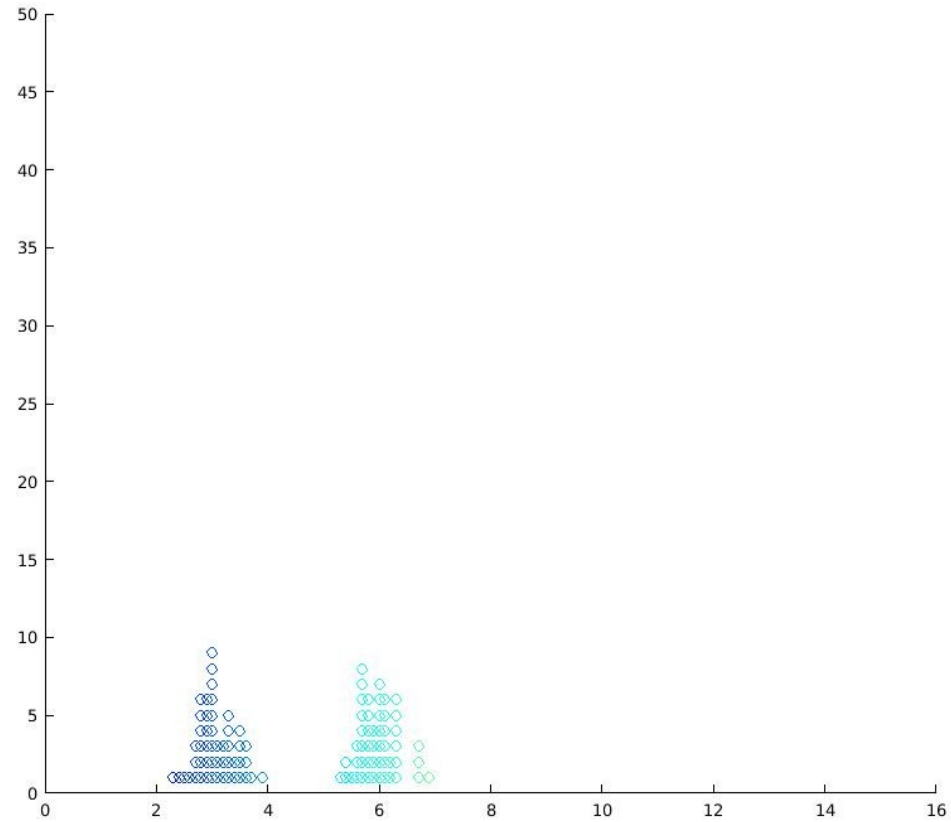
Robot at $t=0$: $\text{bel}(x_0)$



Prediction at $t=1$: $\overline{\text{bel}}(x_1)$



Prediction at $t=2$: $\overline{\text{bel}}(x_2)$



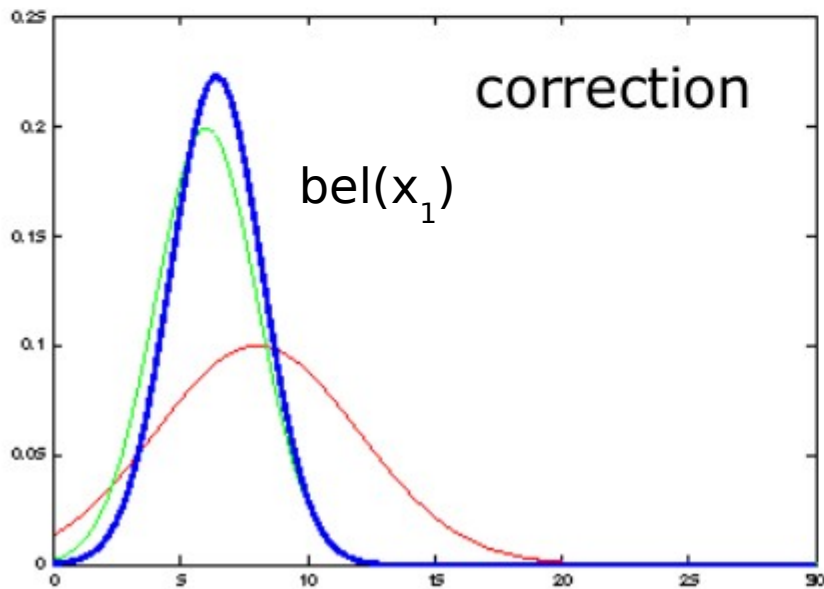
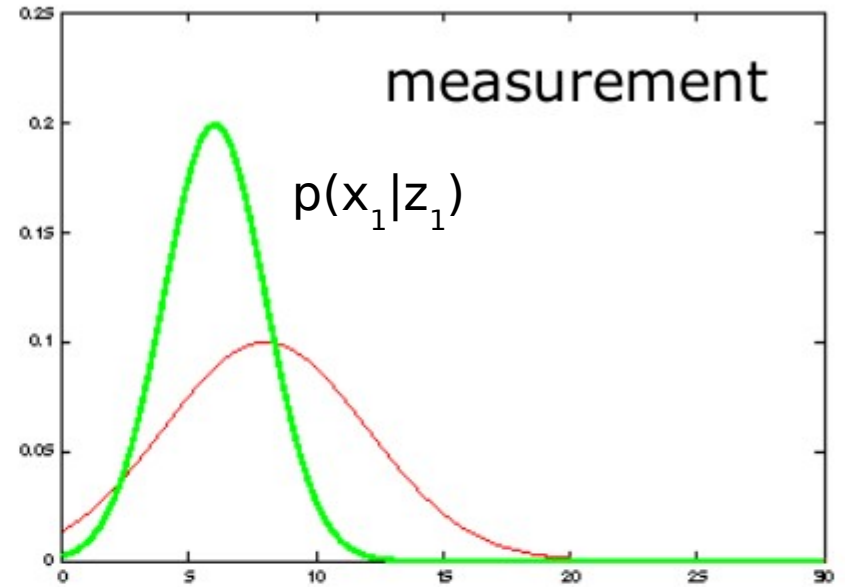
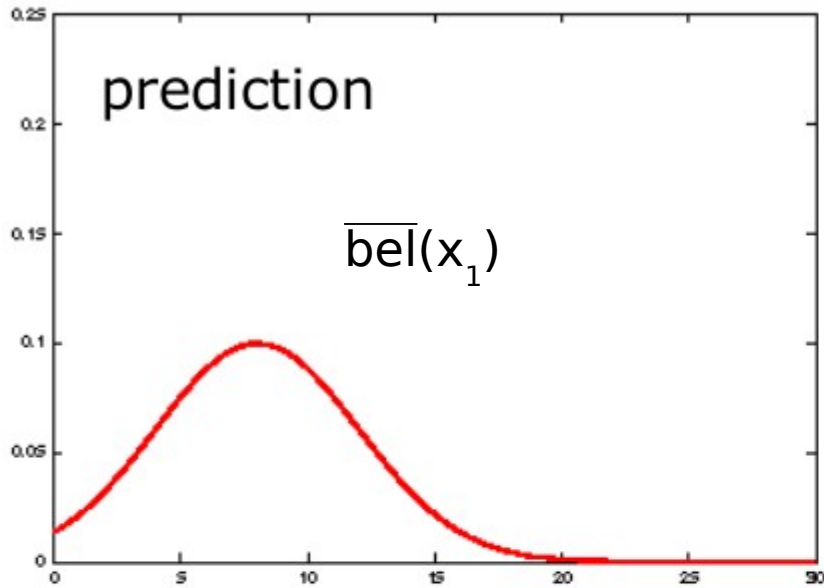
Correcting Our Prediction

- To mitigate the noisiness of our motion model, we use sensor readings z_t to correct our belief distribution.
- Our sensors give us a probability distribution $p(x_t|z_t)$.
- Can't our sensors just tell us where we are?
- **NO!**
 - They're noisy.
 - An individual reading may not be that informative because the world can be ambiguous (e.g., doors look alike).
 - Need to combine information.

Sensor Model

- We should try to model uncertainty in our sensor data.
- Lots of work on sonar and laser rangefinder noise models (e.g., effects of reflections, viewing angle, etc.)
- For visual landmarks:
 - Effects of camera resolution.
 - Distance estimates might have variance proportional to the mean.
 - Bearing estimates might have variance inversely proportional to distance.

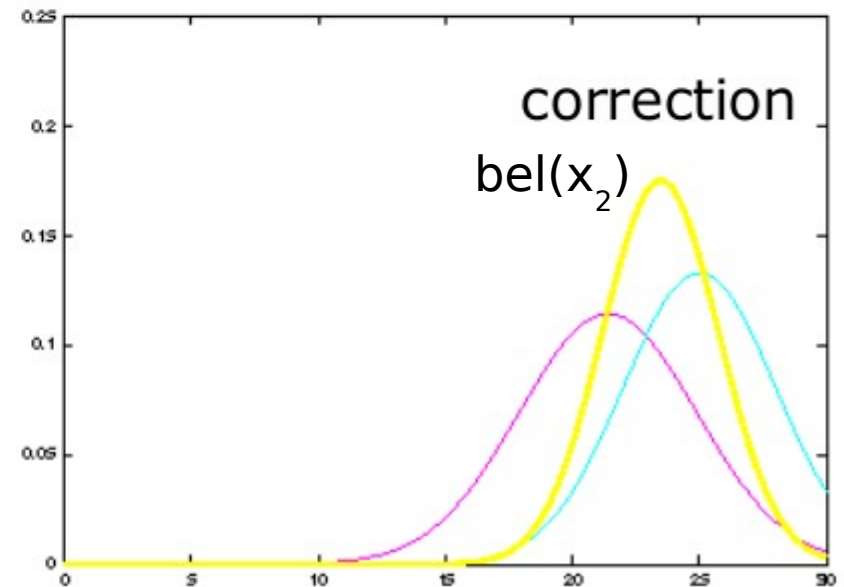
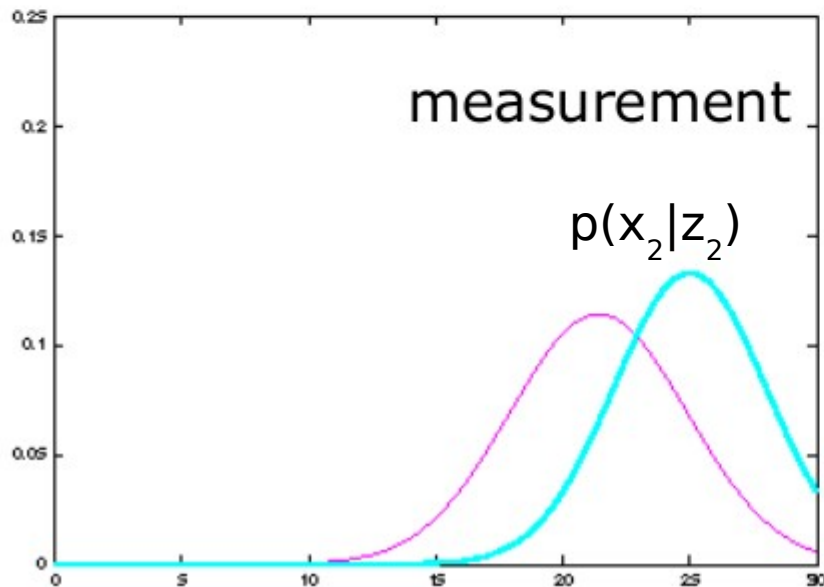
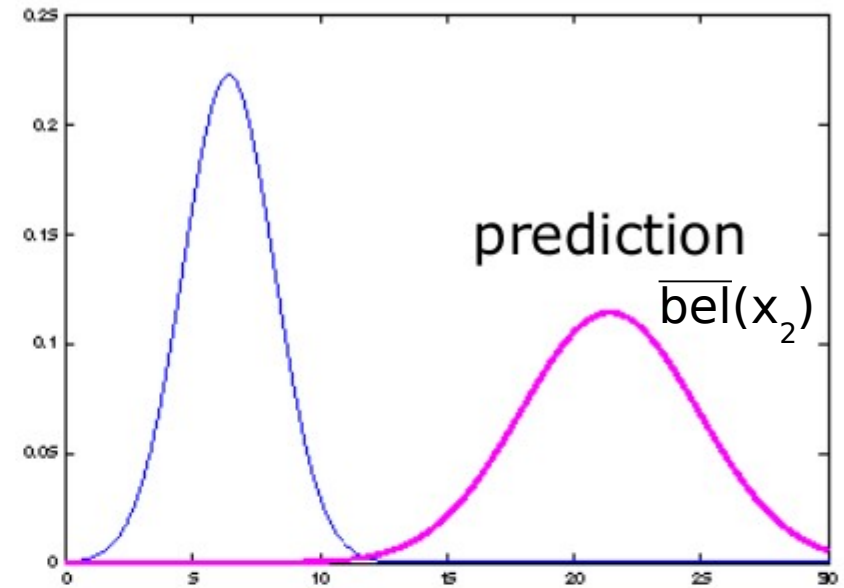
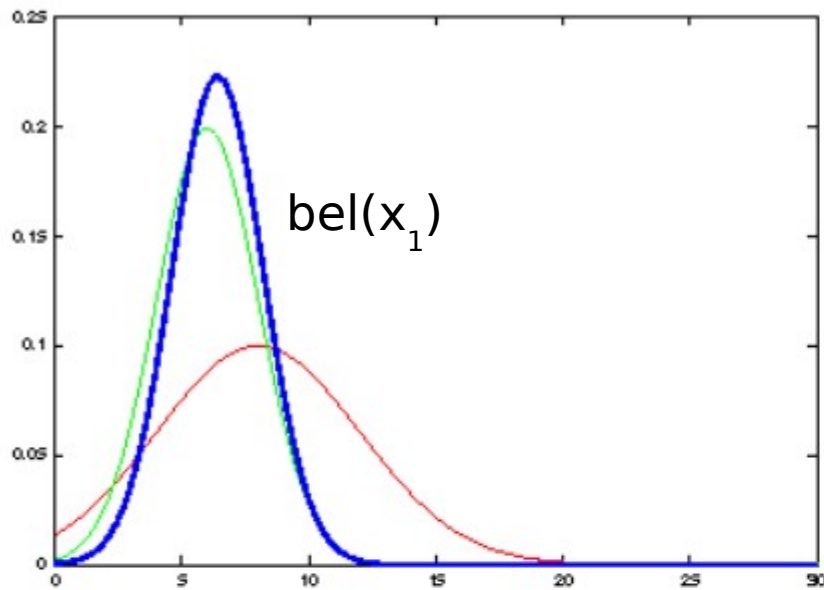
If distributions are gaussian, we can combine them using a **Kalman filter**. Weighting is inversely proportional to variance.



It's a weighted mean!

Slide modified from Burgard et al., "Introduction to Mobile Robotics", 2014, lecture 9: "Bayes Filter - Kalman Filter".

Second iteration: prior belief \rightarrow prediction \rightarrow measurement \rightarrow correction.



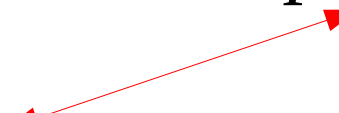
Slide modified from Burgard et al., "Introduction to Mobile Robotics", 2014, lecture 9: "Bayes Filter - Kalman Filter".

Bayesian Filter, part 2

$$\overline{bel}(x_t) = \int p(x_t|x_{t-1}, u_t) \cdot bel(x_{t-1}) dx_{t-1}$$

Sensor reading z_t gives distribution $p(x_t|z_t)$.

Corrected: $bel(x_t) = \eta p(z_t|x_t) \cdot \overline{bel}(x_t)$



η is a normalization constant.

Corrected Sampling Representation

- Distribution $\overline{\text{bel}}(x_t)$ is “corrected” by weight $p(z_t|x_t)$ to give $\text{bel}(x_t)$.
- The *weighted* particles are a sampling representation of the new distribution $p(x_t)$.
- The robot can move around and we can move the particles and update their weights.
- But is this a good representation?
- Particles whose weights become low aren't representing useful hypotheses. Eventually the representation falls apart because we're sampling the wrong regions.

Resampling

- Things break down when too many particles are representing the wrong regions of $\text{bel}(x_t)$, so their weights are low.
- We can fix this by resampling $\text{bel}(x_t)$, giving a fresh set of particles distributed correctly.
- But we have no formula for $\text{bel}(x_t)$, and no direct representation of it.
- So how do we sample from it? *Importance sampling.*

Sampling $y=g(x)$ From An Arbitrary Distribution x

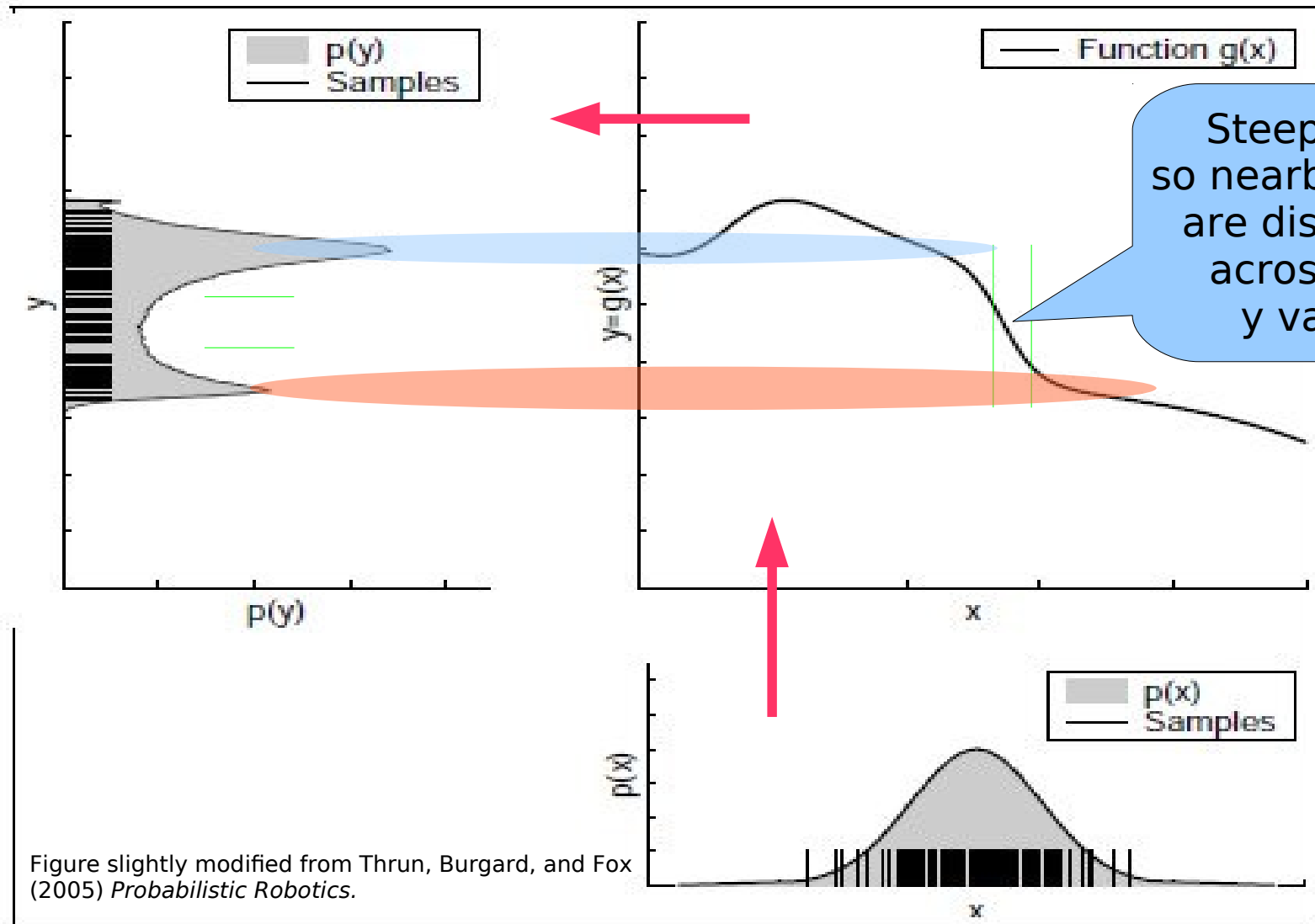
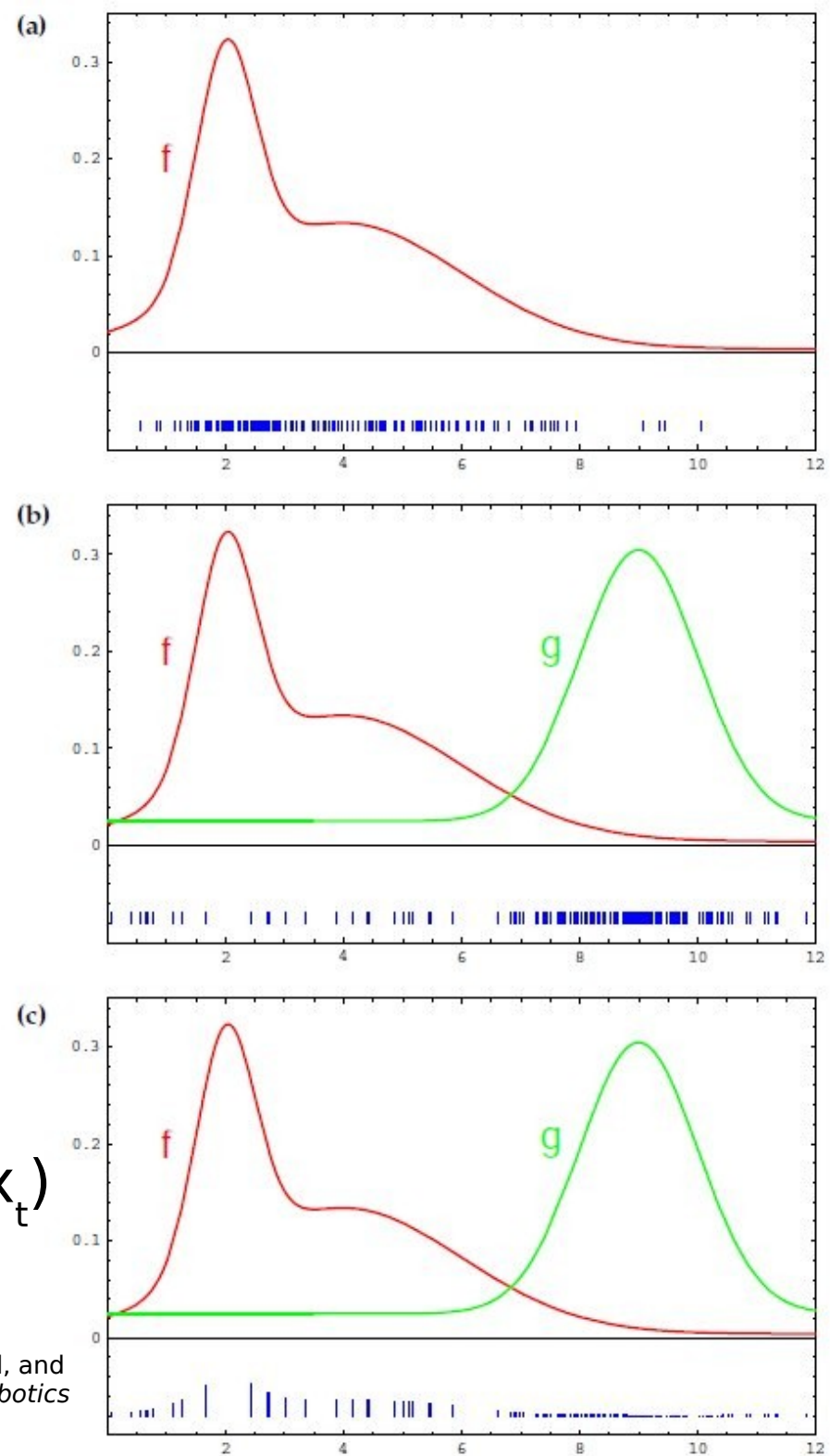


Figure slightly modified from Thrun, Burgard, and Fox (2005) *Probabilistic Robotics*.

Importance Sampling

- Want to sample from f .
- Can only sample from g .
- Weight each sample by $f(x) / g(x)$.
- The weighted samples approximate f .
- g is $\overline{\text{bel}}(x_t)$
- Weighting comes from $p(z_t | x_t)$
- Draw from the weighted sample.

Figure from Thrun, Burgard, and Fox (2005) *Probabilistic Robotics*



Resampling

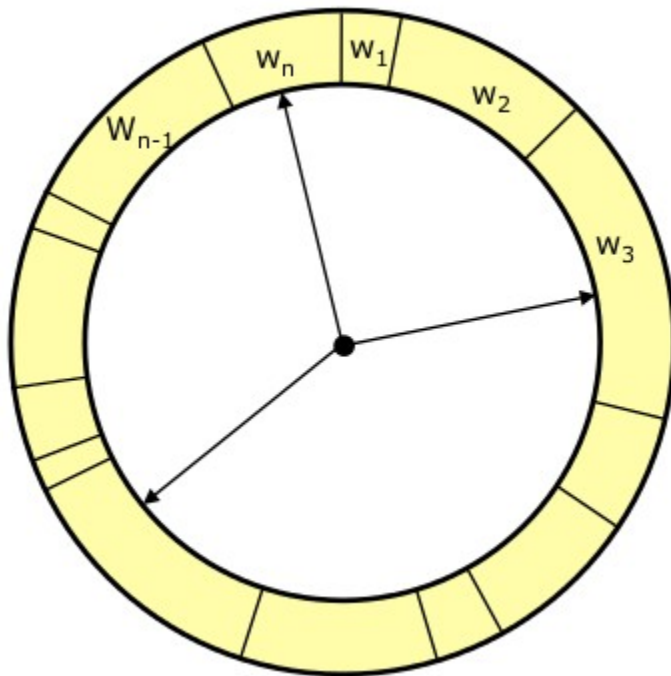
- We don't need to resample on every time step t .
- We can accumulate sensor data for several time steps, so our weights are more accurate. We can use the weights to estimate the robot's location (if unimodal).

$$\hat{x}(t) = \sum_i w_t^{(i)} \cdot x_t^{(i)}$$

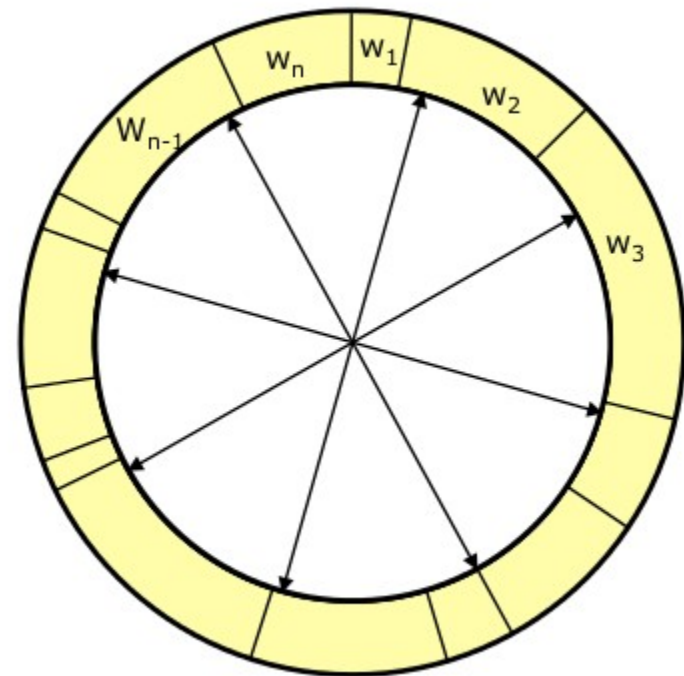
- When to resample?
 - If the variance on the weights is high, then many particles are representing non-useful portions of the space.
 - Resampling redistributes the particles so they are concentrated where the probability density is highest.

How To Resample

- Stochastic universal sampling is a trick for drawing samples from a weighted distribution as fairly as possible (low variance).



3 samples



8 samples

Image from Burgard et al., "Introduction to Mobile Robotics", 2014, lecture 12: "Bayes Filter - Particle Filter and Monte Carlo Localization".

Weighting in a Corridor

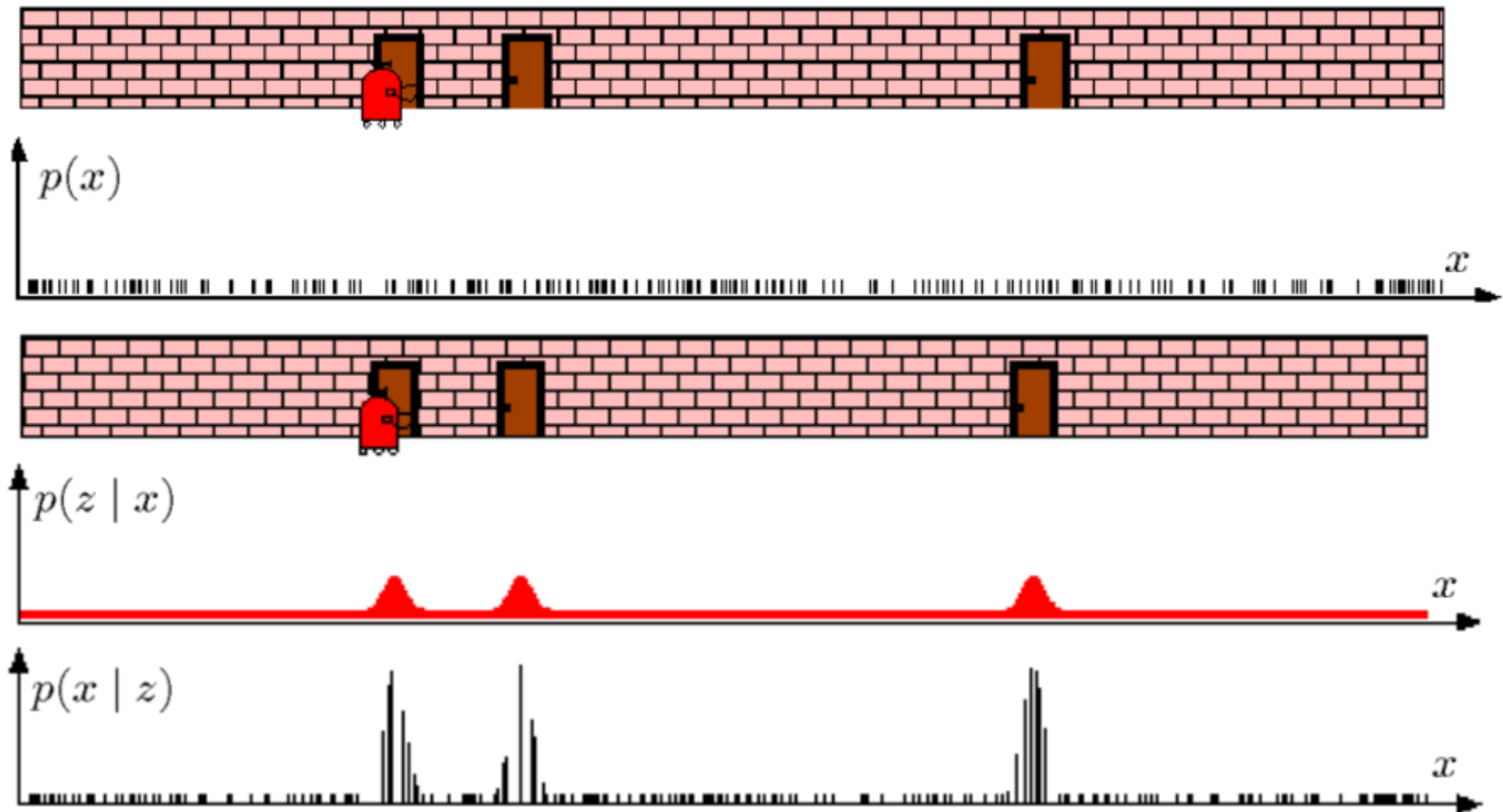


Image from Burgard et al., "Introduction to Mobile Robotics", 2014,
lecture 12: "Bayes Filter - Particle Filter and Monte Carlo Localization".

Resampling and Motion

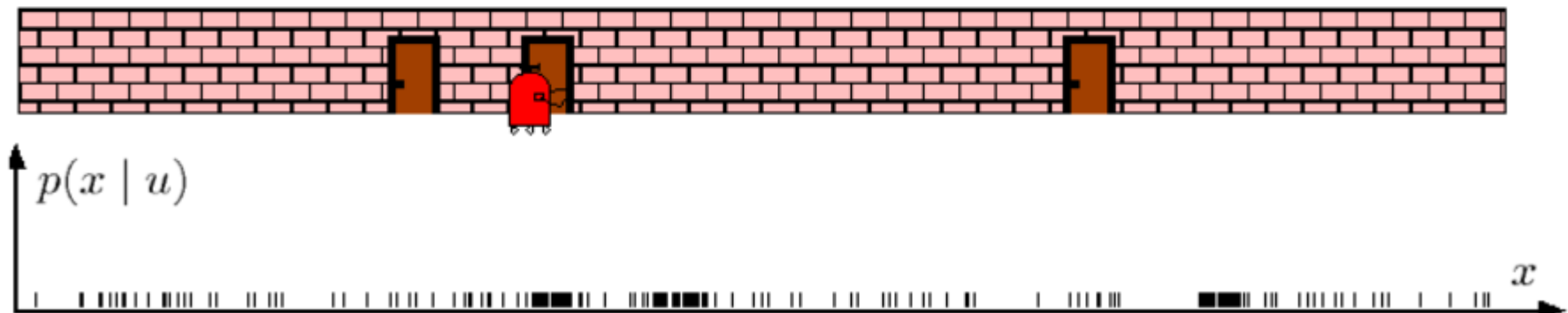
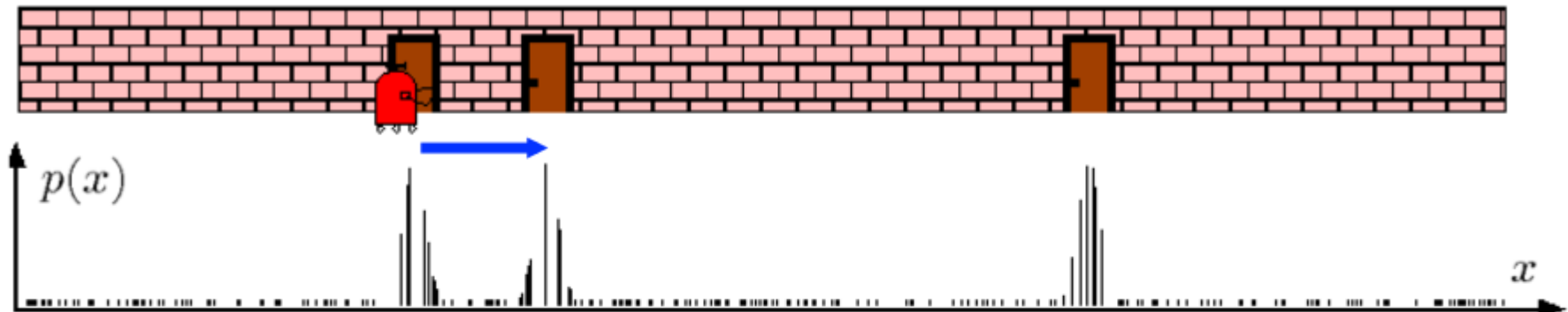


Image from Burgard et al., "Introduction to Mobile Robotics", 2014,
lecture 12: "Bayes Filter - Particle Filter and Monte Carlo Localization".

Sensing and Weighting

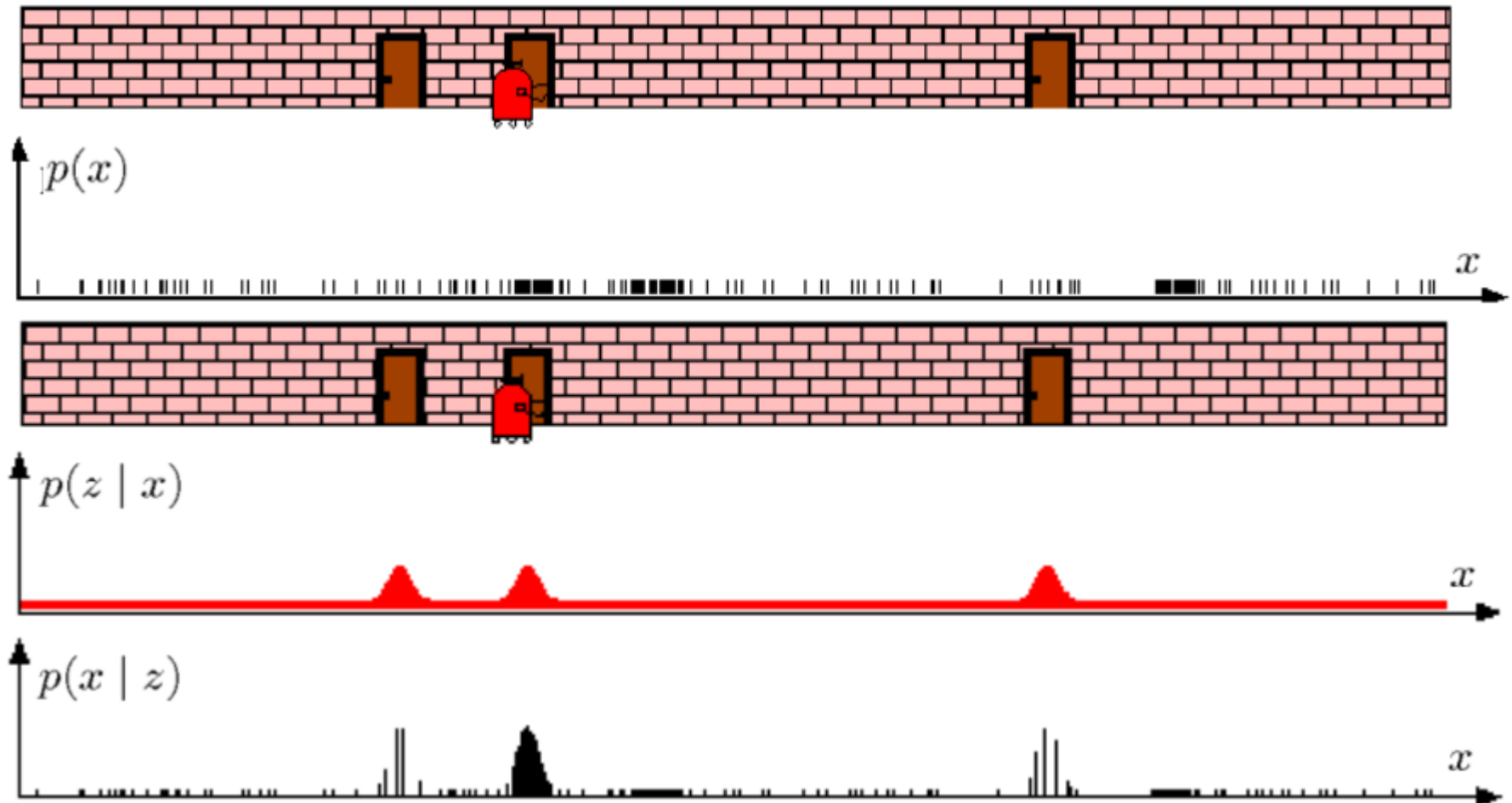


Image from Burgard et al., "Introduction to Mobile Robotics", 2014,
lecture 12: "Bayes Filter - Particle Filter and Monte Carlo Localization".

Resampling and Motion

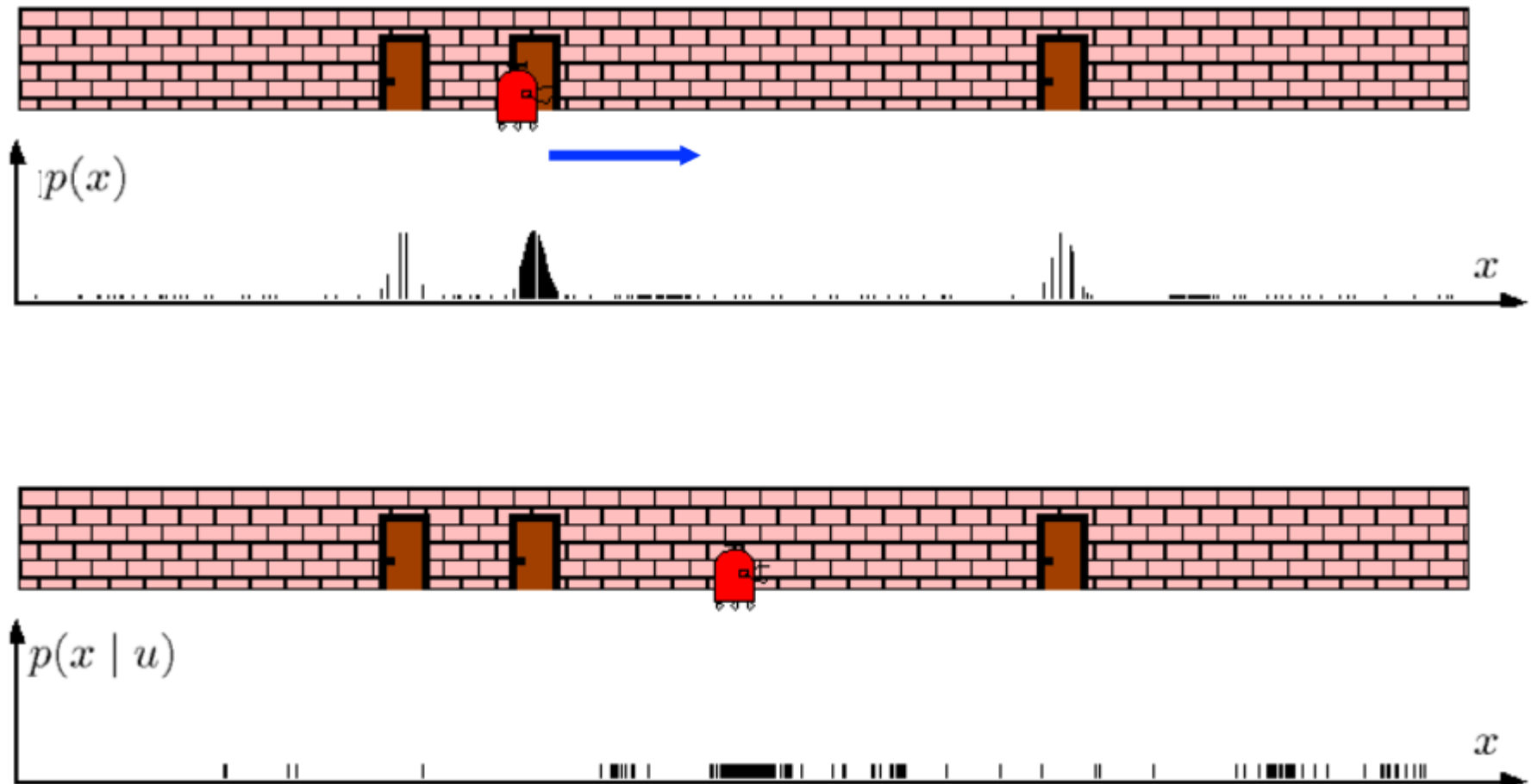


Image from Burgard et al., "Introduction to Mobile Robotics", 2014,
lecture 12: "Bayes Filter - Particle Filter and Monte Carlo Localization".

Summary

- Particle filters are the preferred method for robot localization in the real world.
- Robot pose typically encoded as (x, y, θ) .
- A map is needed to define how sensor values indicate locations. But what if we don't have a map?
- SLAM: Simultaneous Localization and Mapping.
- Particles can be used to represent hypotheses about the map as well as about the robot's location.