Tracking Objects with Dynamics

Computer Vision

CS 543 / ECE 549

University of Illinois

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some slides from Lana Lazebnik, Kristen Grauman, Deva Ramanan, Derek Hoiem

Today: Tracking Objects

Goal: Locating a moving object/part across video frames

This Class:

- Examples and Applications
- Overview of probabilistic tracking
- Kalman Filter
- Particle Filter

Tracking Examples

Traffic: http://www.youtube.com/watch?v=dlZEakHcD_o

Soccer: http://www.youtube.com/watch?v=ZqQIItFAnxg

Face: http://www.youtube.com/watch?v=i_bZNVmhJ2o

Body: http://www.youtube.com/watch?v=gRyo-DM2F6E

Eye: http://www.youtube.com/watch?v=NCtYdUEMotg

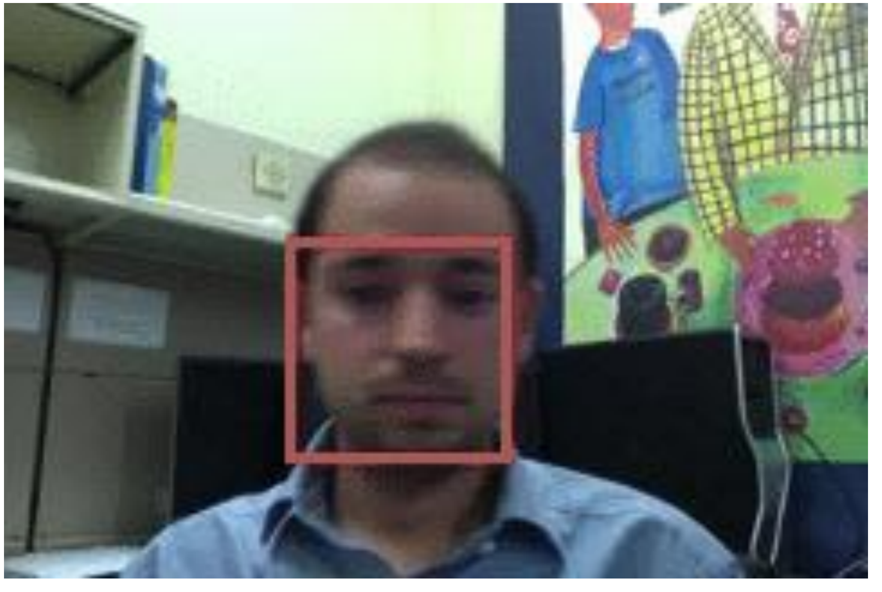
Gaze: http://www.youtube.com/watch?v=-G6Rw5cU-1c

Further applications

- Motion capture
- Augmented Reality
- Action Recognition
- Security, traffic monitoring
- Video Compression
- Video Summarization
- Medical Screening

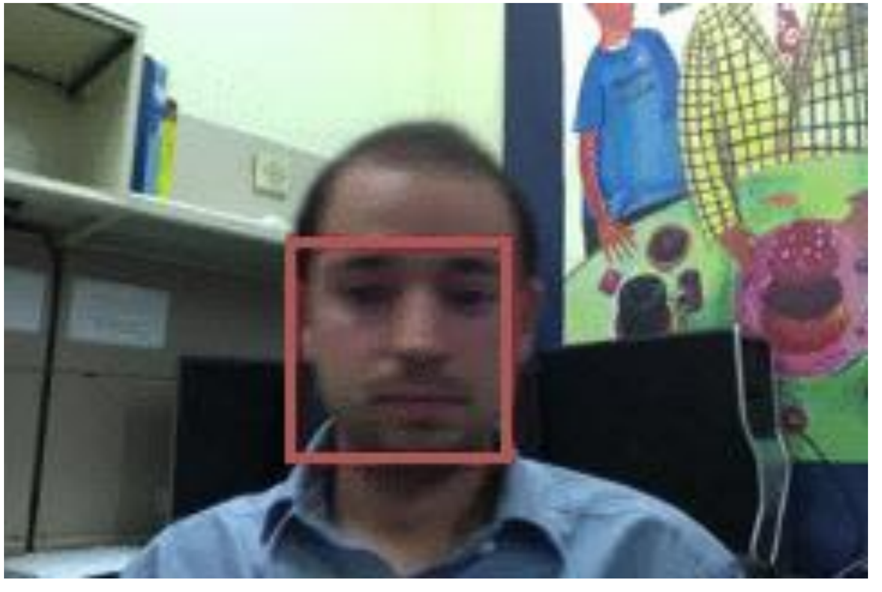
Things that make visual tracking difficult

- Small, few visual features
- Erratic movements, Moving very quickly
- Occlusions, leaving and coming back
- Surrounding similar-looking objects



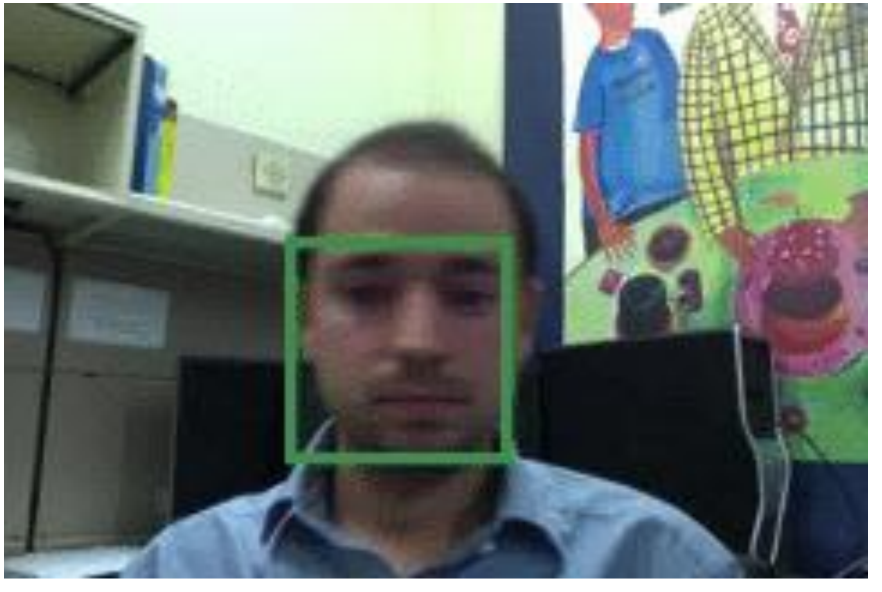
Strategies for tracking

- Tracking by repeated detection
  - Works well if object is easily detectable (e.g., face or colored glove) and there is only one
  - Need some way to link up detections
  - Best you can do, if you can't predict motion



Tracking with dynamics

- Key idea: Based on a model of expected motion, predict where objects will occur in next frame, before even seeing the image
  - Restrict search for the object
  - measurement noise is reduced by trajectory smoothness
  - Robustness to missing or weak observations

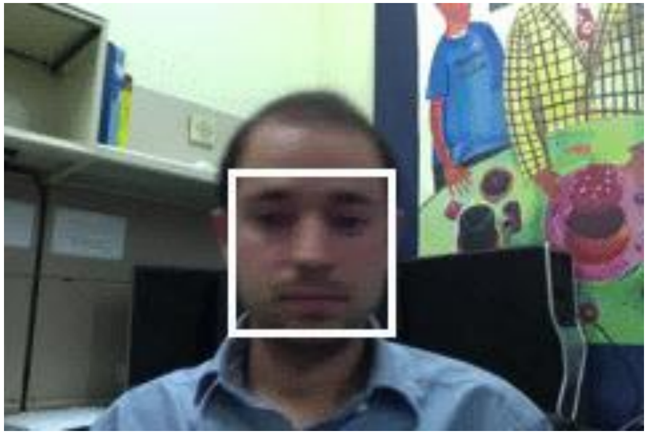


Strategies for tracking

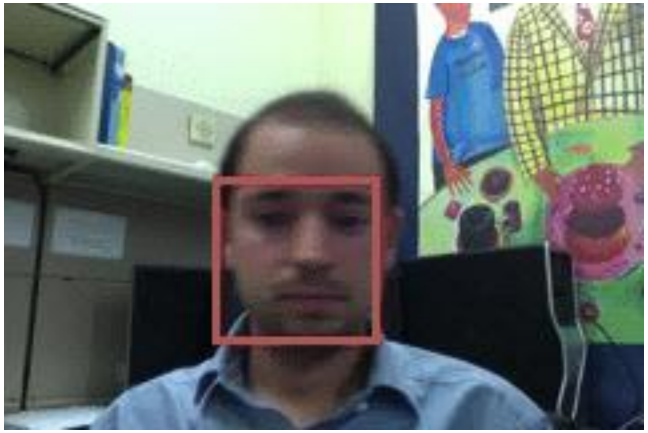
- Tracking with motion prediction
  - Predict the object's state in the next frame
  - **Kalman filtering**: next state can be linearly predicted from current state (Gaussian)
  - **Particle filtering**: sample multiple possible states of the object (non-parametric, good for clutter)

General model for tracking

- ***state** X*: The actual state of the moving object that we want to estimate
  - State could be any combination of position, pose, viewpoint, velocity, acceleration, etc.



- ***observations** Y*: Our actual measurement or observation of state X. Observation can be very noisy



- At each time t, the state changes to X_t and we get a new observation Y_t

Steps of tracking

- **Prediction:** What is the next state of the object given past measurements?

$$P\left(X_t \middle| Y_0 = y_0, \ldots, Y_{t-1} = y_{t-1}\right)$$

Steps of tracking

- **Prediction:** What is the next state of the object given past measurements?

$$P\left(X_t \middle| Y_0 = y_0, \ldots, Y_{t-1} = y_{t-1}\right)$$

- **Correction:** Compute an updated estimate of the state from prediction and measurements

$$P\left(X_t \middle| Y_0 = y_0, \ldots, Y_{t-1} = y_{t-1}, Y_t = y_t\right)$$

Simplifying assumptions

- Only the immediate past matters

$$P\left(X_t \middle| X_0, \ldots, X_{t-1}\right) = \boxed{P\left(X_t \middle| X_{t-1}\right)}$$

dynamics model

Simplifying assumptions

- Only the immediate past matters

$$P(X_t | X_0, \ldots, X_{t-1}) = \boxed{P(X_t | X_{t-1})}$$

dynamics model

- Measurements depend only on the current state $P(Y_t | X_0, Y_0 \ldots, X_{t-1}, Y_{t-1}, X_t) = \boxed{P(Y_t | X_t)}$

observation model

Simplifying assumptions

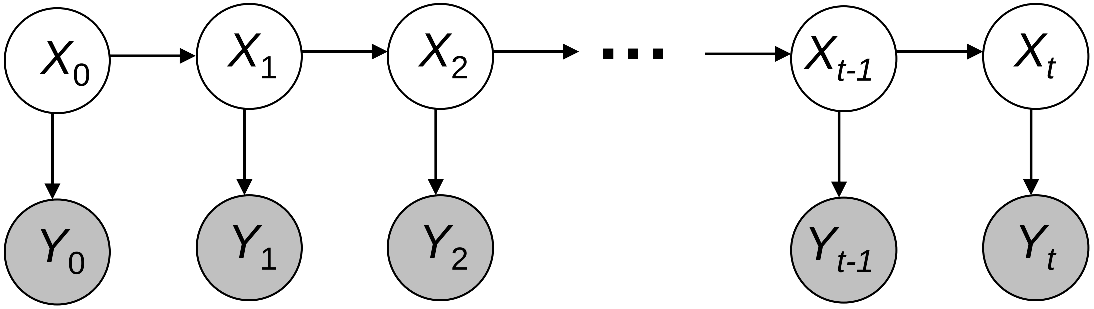
- Only the immediate past matters

$$P(X_t | X_0, \ldots, X_{t-1}) = \boxed{P(X_t | X_{t-1})}$$

dynamics model

- Measurements depend only on the current state $P(Y_t | X_0, Y_0 \ldots, X_{t-1}, Y_{t-1}, X_t) = \boxed{P(Y_t | X_t)}$

observation model



Problem statement

- We have models for
  Likelihood of next state given current state: $P(X_t | X_{t-1})$
  Likelihood of observation given the state: $P(Y_t | X_t)$

- We want to recover, for each t: $P(X_t | y_0, \ldots, y_t)$

Tracking as induction

- Base case:
  - Start with initial prior that predicts state in absence of any evidence: $P(X_0)$
  - For the first frame, *correct* this given the first measurement: $Y_0 = y_0$

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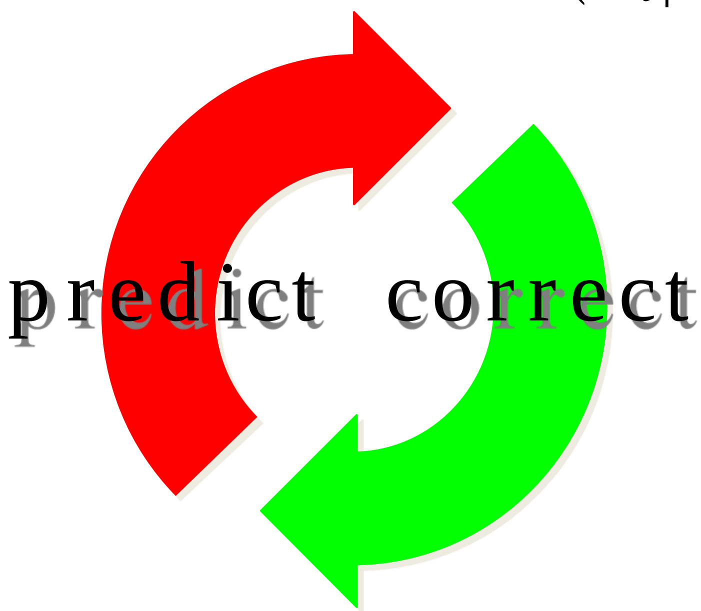
$$P(X_0 \mid Y_0 = y_0) = \frac{P(y_0 \mid X_0) P(X_0)}{P(y_0)} \propto P(y_0 \mid X_0) P(X_0)$$

Tracking as induction

- Base case:
  - Start with initial prior that predicts state in absence of any evidence: $P(X_0)$
  - For the first frame, *correct* this given the first measurement: $Y_0 = y_0$
- Given corrected estimate for frame *t-1*:
  - Predict for frame t ➔ $P\left(X_t \middle| y_0, \ldots, y_{t-1}\right)$
  - Observe y_t; Correct for frame t ➔ $P\left(X_t \middle| y_0, \ldots, y_{t-1}, y_t\right)$



Prediction

- Prediction involves representing $P\left(X_t \middle| y_0, \ldots, y_{t-1}\right)$ given $P\left(X_{t-1} \middle| y_0, \ldots, y_{t-1}\right)$

$$P\left(X_t \middle| y_0, \ldots, y_{t-1}\right)$$
$$= \int P\left(X_t, X_{t-1} \middle| y_0, \ldots, y_{t-1}\right) dX_{t-1}$$

Law of total probability

Prediction

- Prediction involves representing $P(X_t | y_0, \ldots, y_{t-1})$ given $P(X_{t-1} | y_0, \ldots, y_{t-1})$

$$
\begin{aligned}
&P(X_t | y_0, \ldots, y_{t-1}) \\
&= \int P(X_t, X_{t-1} | y_0, \ldots, y_{t-1}) dX_{t-1} \\
&= \int P(X_t \mid X_{t-1}, y_0, \ldots, y_{t-1}) P(X_{t-1} \mid y_0, \ldots, y_{t-1}) dX_{t-1}
\end{aligned}
$$

Conditioning on X_{t-1}

Prediction

- Prediction involves representing $P\left(X_t \middle| y_0, \ldots, y_{t-1}\right)$ given $P\left(X_{t-1} \middle| y_0, \ldots, y_{t-1}\right)$

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\begin{aligned}
&P\left(X_t \middle| y_0, \ldots, y_{t-1}\right) \\
&= \int P\left(X_t, X_{t-1} \middle| y_0, \ldots, y_{t-1}\right) dX_{t-1} \\
&= \int P\left(X_t \mid X_{t-1}, y_0, \ldots, y_{t-1}\right) P\left(X_{t-1} \mid y_0, \ldots, y_{t-1}\right) dX_{t-1} \\
&= \int P\left(X_t \mid X_{t-1}\right) P\left(X_{t-1} \mid y_0, \ldots, y_{t-1}\right) dX_{t-1}
\end{aligned}
$$

Independence assumption

Prediction

- Prediction involves representing $P\left(X_t \middle| y_0, \ldots, y_{t-1}\right)$ given $P\left(X_{t-1} \middle| y_0, \ldots, y_{t-1}\right)$

$$
\begin{aligned}
& P\left(X_t \middle| y_0, \ldots, y_{t-1}\right) \\
& = \int P\left(X_t, X_{t-1} \middle| y_0, \ldots, y_{t-1}\right) dX_{t-1} \\
& = \int P\left(X_t \mid X_{t-1}, y_0, \ldots, y_{t-1}\right) P\left(X_{t-1} \mid y_0, \ldots, y_{t-1}\right) dX_{t-1} \\
& = \int \underbrace{P\left(X_t \mid X_{t-1}\right)}_{\text{dynamics model}} \underbrace{P\left(X_{t-1} \mid y_0, \ldots, y_{t-1}\right)}_{\text{corrected estimate from previous step}} dX_{t-1}
\end{aligned}
$$

Correction

- Correction involves computing $P\left(X_t \middle| y_0, \ldots, y_t\right)$ given predicted value $P\left(X_t \middle| y_0, \ldots, y_{t-1}\right)$

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$$P\left(X_t \middle| y_0, \ldots, y_t\right) = \frac{P\left(y_t \mid X_t, y_0, \ldots, y_{t-1}\right)}{P\left(y_t \mid y_0, \ldots, y_{t-1}\right)} P\left(X_t \mid y_0, \ldots, y_{t-1}\right)$$

Bayes' Rule

Correction

- Correction involves computing $P(X_t | y_0, \ldots, y_t)$ given predicted value $P(X_t | y_0, \ldots, y_{t-1})$

$$P(X_t | y_0, \ldots, y_t)$$
$$= \frac{P(y_t \mid X_t, y_0, \ldots, y_{t-1})}{P(y_t \mid y_0, \ldots, y_{t-1})} P(X_t \mid y_0, \ldots, y_{t-1})$$
$$= \frac{P(y_t \mid X_t) P(X_t \mid y_0, \ldots, y_{t-1})}{P(y_t \mid y_0, \ldots, y_{t-1})}$$

Independence assumption
(observation y_t directly depends only on state X_t)

Correction

- Correction involves computing $P\left(X_t \middle| y_0,\ldots,y_t\right)$ given predicted value $P\left(X_t \middle| y_0,\ldots,y_{t-1}\right)$

$$
\begin{aligned}
&P\left(X_t \middle| y_0,\ldots,y_t\right) \\
&\quad = \frac{P\left(y_t \mid X_t, y_0,\ldots,y_{t-1}\right)}{P\left(y_t \mid y_0,\ldots,y_{t-1}\right)} P\left(X_t \mid y_0,\ldots,y_{t-1}\right) \\
&\quad = \frac{P\left(y_t \mid X_t\right) P\left(X_t \mid y_0,\ldots,y_{t-1}\right)}{P\left(y_t \mid y_0,\ldots,y_{t-1}\right)} \\
&\quad = \frac{P\left(y_t \mid X_t\right) P\left(X_t \mid y_0,\ldots,y_{t-1}\right)}{\int P\left(y_t \mid X_t\right) P\left(X_t \mid y_0,\ldots,y_{t-1}\right) dX_t}
\end{aligned}
$$

Conditioning on X_t

Correction

- Correction involves computing $P\left(X_t \middle| y_0, \ldots, y_t\right)$ given predicted value $P\left(X_t \middle| y_0, \ldots, y_{t-1}\right)$

$$P\left(X_t \middle| y_0, \ldots, y_t\right)$$

$$= \frac{P\left(y_t \mid X_t, y_0, \ldots, y_{t-1}\right)}{P\left(y_t \mid y_0, \ldots, y_{t-1}\right)} P\left(X_t \mid y_0, \ldots, y_{t-1}\right)$$

$$= \frac{P\left(y_t \mid X_t\right) P\left(X_t \mid y_0, \ldots, y_{t-1}\right)}{P\left(y_t \mid y_0, \ldots, y_{t-1}\right)}$$

observation model

predicted estimate

$$= \frac{P\left(y_t \mid X_t\right) P\left(X_t \mid y_0, \ldots, y_{t-1}\right)}{\int P\left(y_t \mid X_t\right) P\left(X_t \mid y_0, \ldots, y_{t-1}\right) dX_t}$$

normalization factor

Summary: Prediction and correction

Prediction:

$$P(X_t \mid y_0, \ldots, y_{t-1}) = \int \underbrace{P(X_t \mid X_{t-1})}_{\text{dynamics model}} \underbrace{P(X_{t-1} \mid y_0, \ldots, y_{t-1})}_{\text{corrected estimate from previous step}} dX_{t-1}$$

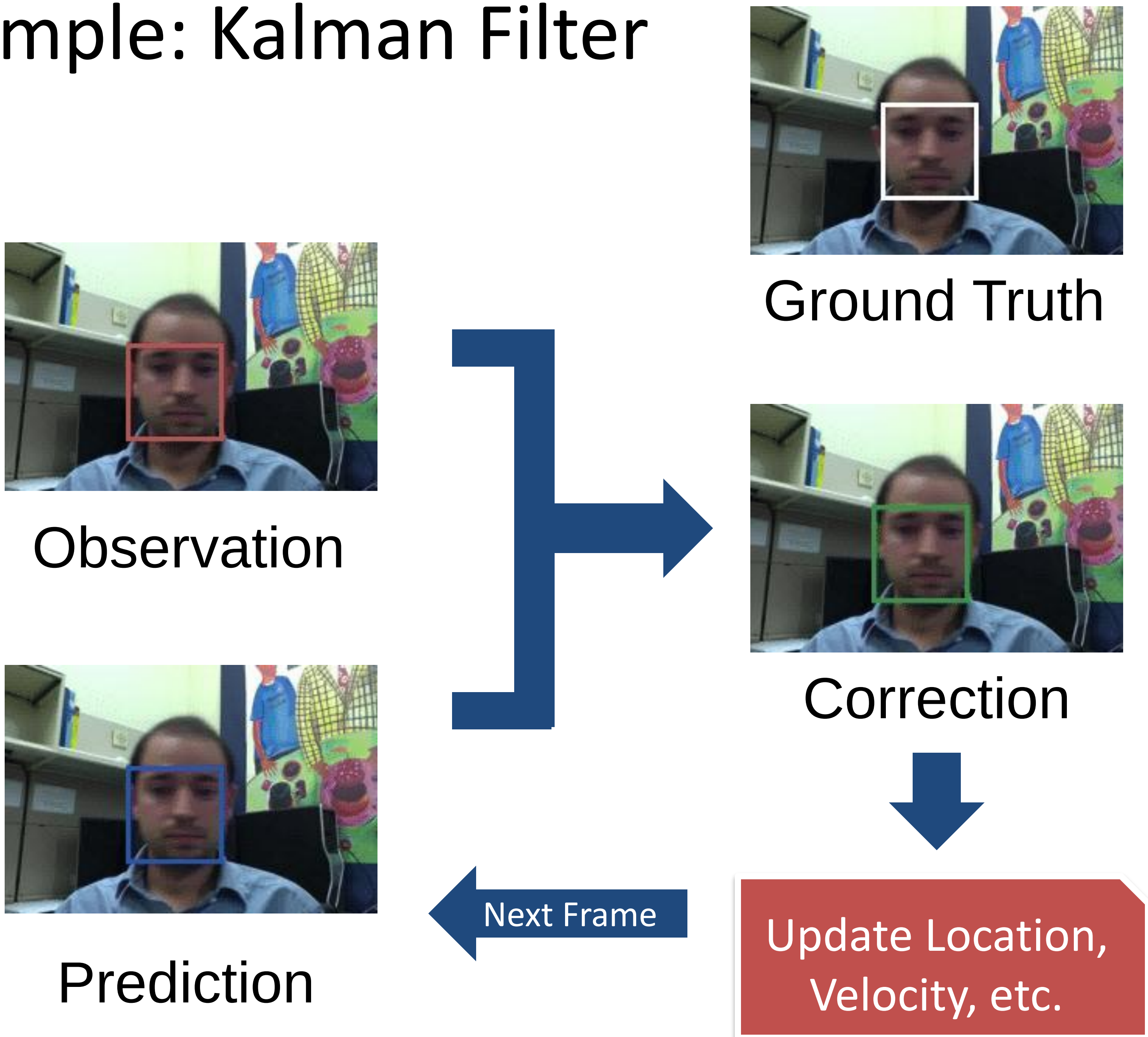
Correction:

$$P(X_t \mid y_0, \ldots, y_t) = \frac{\overbrace{P(y_t \mid X_t)}^{\text{observation model}} \overbrace{P(X_t \mid y_0, \ldots, y_{t-1})}^{\text{predicted estimate}}}{\int P(y_t \mid X_t) P(X_t \mid y_0, \ldots, y_{t-1}) dX_t}$$

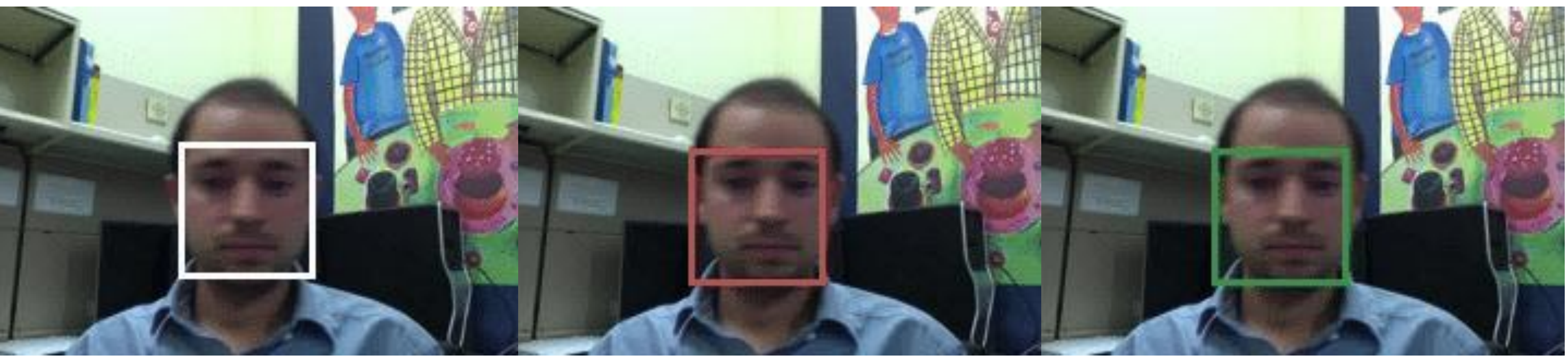
The Kalman filter

- Linear dynamics model: state undergoes linear transformation plus Gaussian noise
- Observation model: measurement is linearly transformed state plus Gaussian noise
- The predicted/corrected state distributions are Gaussian
  - You only need to maintain the mean and covariance
  - The calculations are easy (all the integrals can be done in closed form)

Example: Kalman Filter

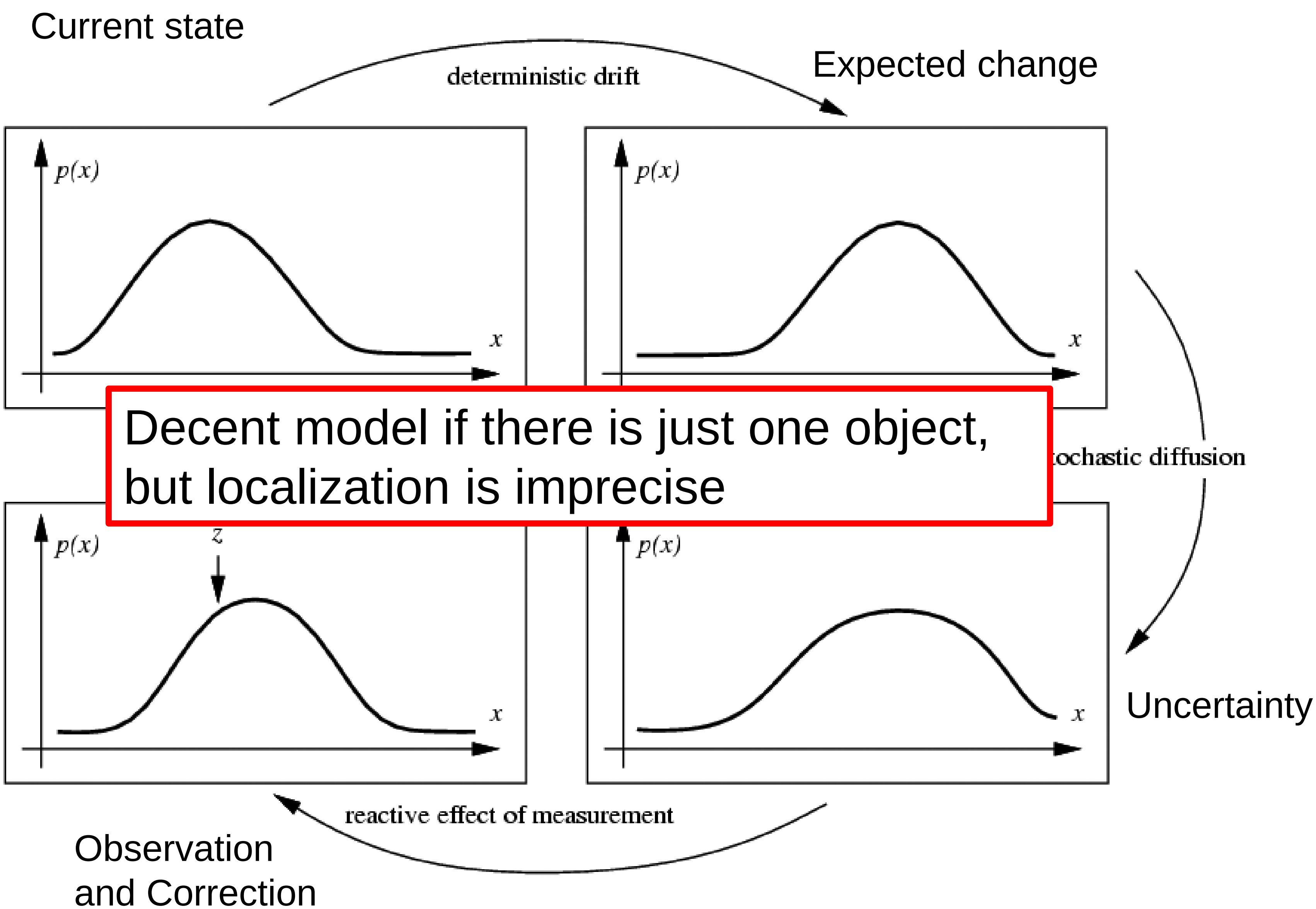


Comparison



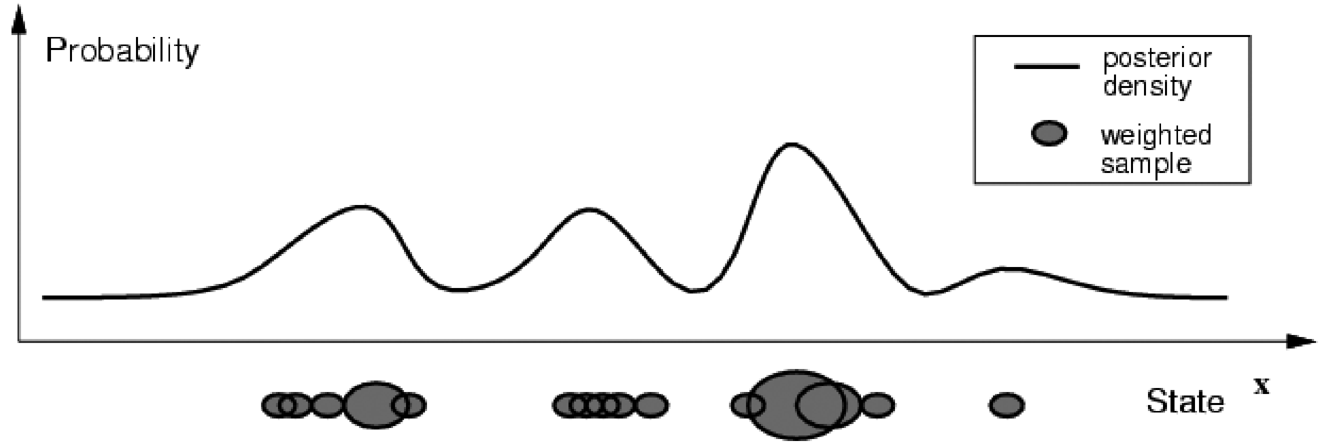
Ground Truth | Observation | Correction

Propagation of Gaussian densities



Decent model if there is just one object, but localization is imprecise

Particle filtering

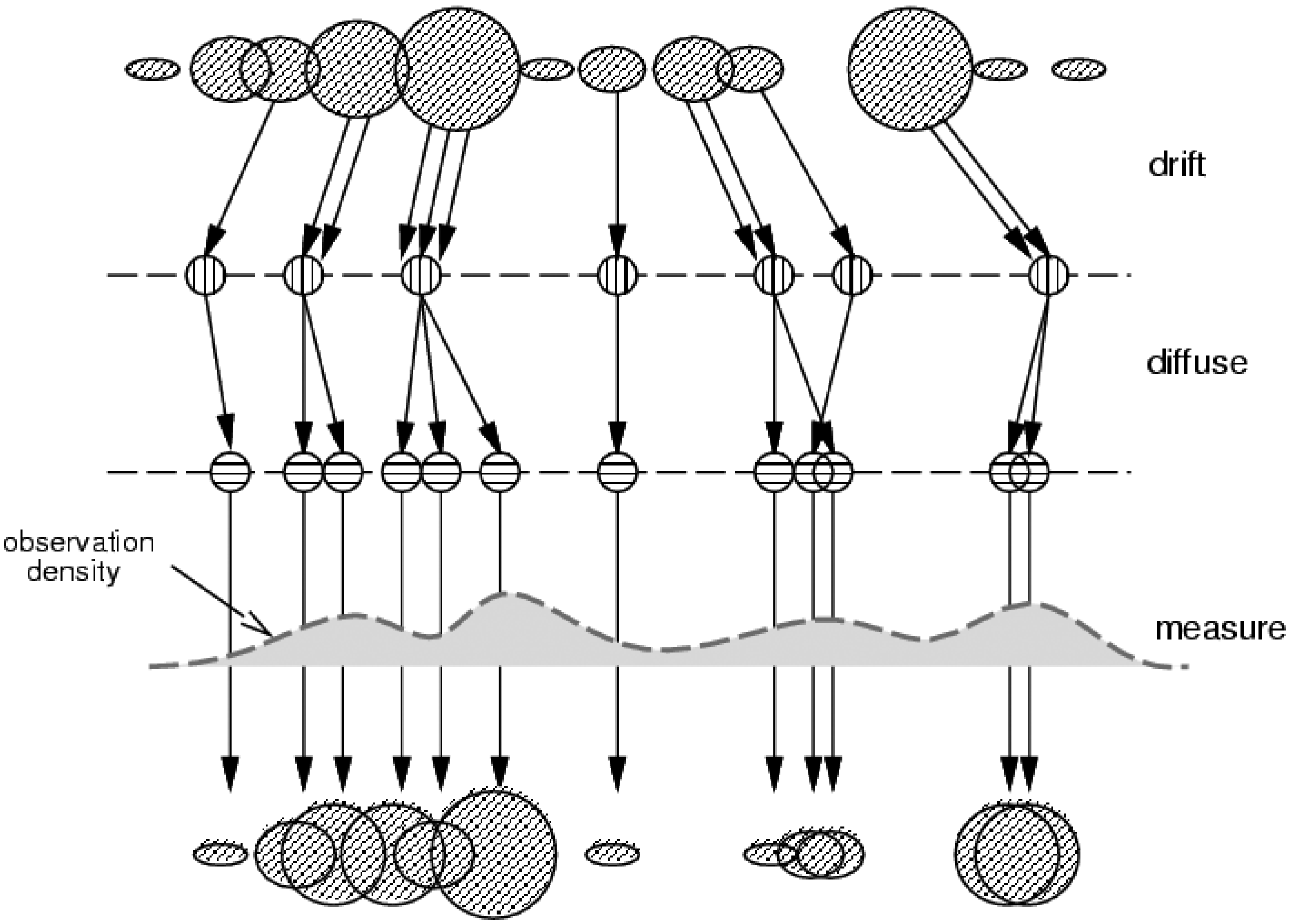


Represent the state distribution non-parametrically

- Prediction: Sample possible values X_{t-1} for the previous state
- Correction: Compute likelihood of X_t based on weighted samples and $P(y_t|X_t)$

M. Isard and A. Blake, CONDENSATION -- conditional density propagation for visual tracking, IJCV 29(1):5-28, 1998

Particle filtering



Start with weighted samples from previous time step

Sample and shift according to dynamics model

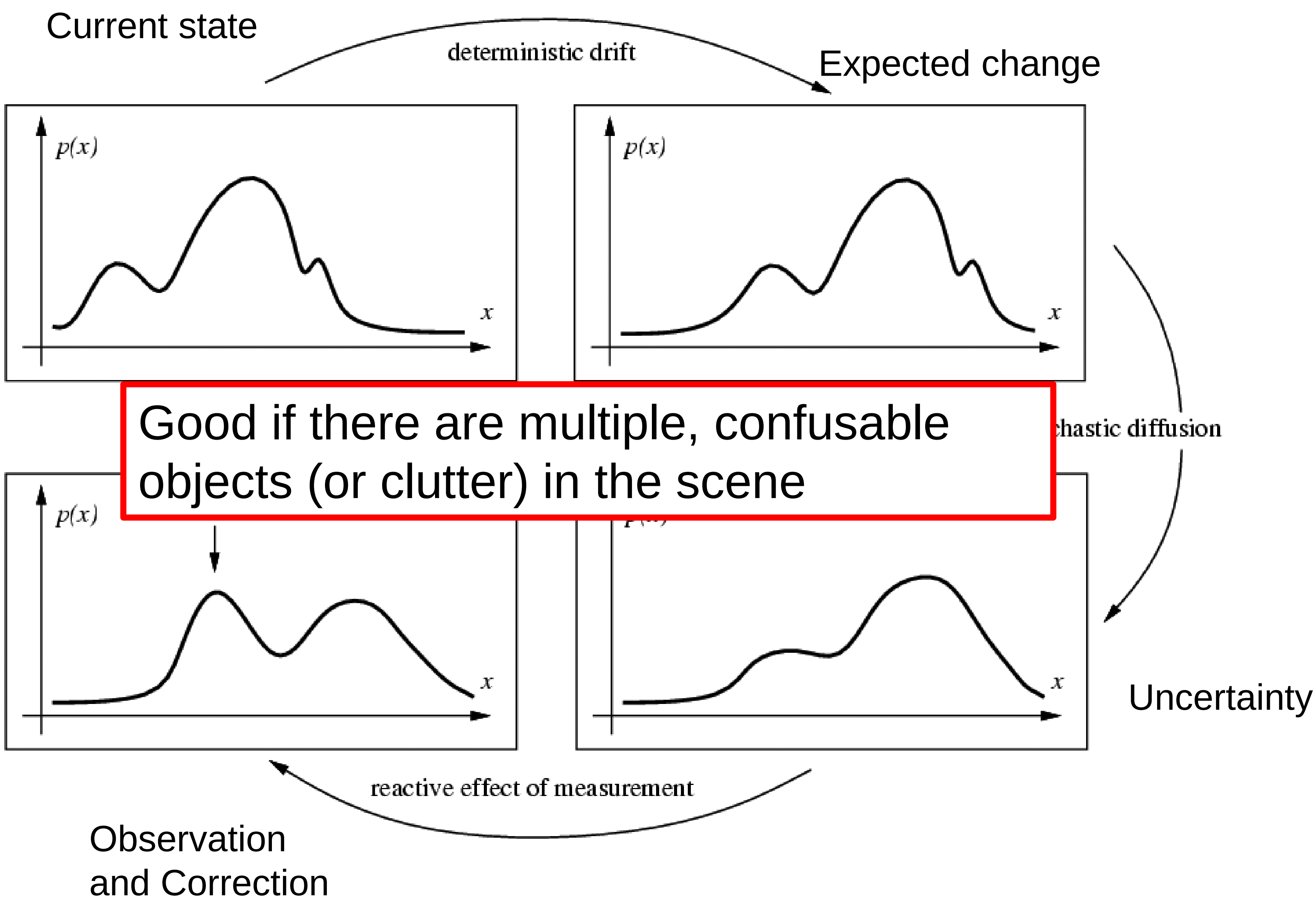
Spread due to randomness; this is predicted density $P(X_t|Y_{t-1})$

Weight the samples according to observation density

Arrive at corrected density estimate $P(X_t|Y_t)$

M. Isard and A. Blake, [CONDENSATION -- conditional density propagation for visual tracking](), IJCV 29(1):5-28, 1998

Propagation of non-parametric densities



Good if there are multiple, confusable objects (or clutter) in the scene

Particle filtering results

People: http://www.youtube.com/watch?v=wCMk-pHzScE

Hand: http://www.youtube.com/watch?v=tIjufInUqZM

Tracking issues

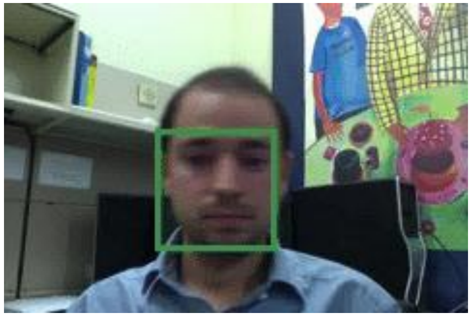
- Initialization
  - Manual
  - Background subtraction
  - Detection

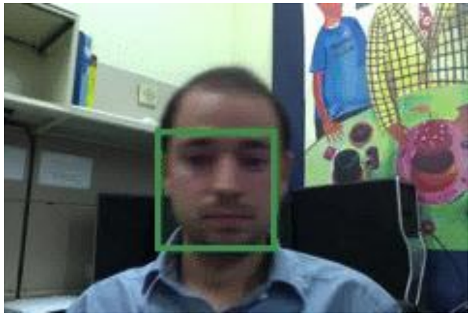
Tracking issues

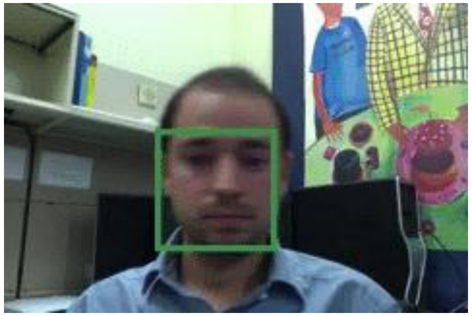
- Initialization
- Getting observation and dynamics models
  - Observation model: match a template or use a trained detector
  - Dynamics model: usually specify using domain knowledge

Tracking issues

- Initialization
- Obtaining observation and dynamics model
- Uncertainty of prediction vs. correction
  - If the dynamics model is too strong, will end up ignoring the data
  - If the observation model is too strong, tracking is reduced to repeated detection





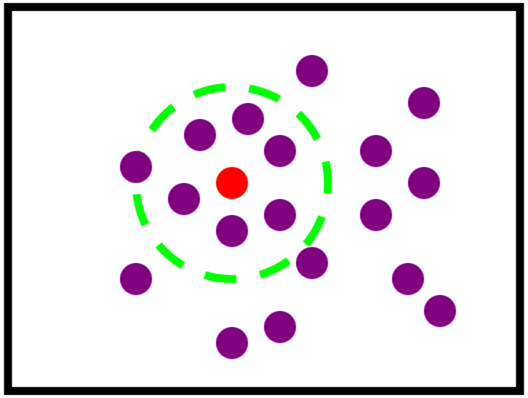


Too strong dynamics model

Too strong observation model

Tracking issues

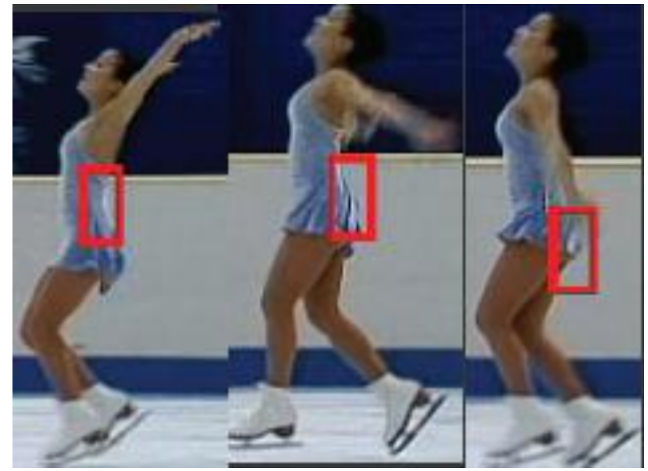
- Initialization
- Getting observation and dynamics models
- Prediction vs. correction
- Data association
  - When tracking multiple objects, need to assign right objects to right tracks (particle filters good for this)



Tracking issues

- Initialization
- Getting observation and dynamics models
- Prediction vs. correction
- Data association
- Drift
  - Errors can accumulate over time

Drift



D. Ramanan, D. Forsyth, and A. Zisserman. [Tracking People by Learning their Appearance](). PAMI 2007.

Things to remember

- Tracking objects = detection + prediction

- Probabilistic framework
  - Predict next state
  - Update current state based on observation

- Two simple but effective methods
  - Kalman filters: Gaussian distribution
  - Particle filters: multimodal distribution

Next class: action recognition

- Action recognition
  - What is an “action”?
  - How can we represent movement?
  - How do we incorporate motion, pose, and nearby objects?