Artificial Intelligence

14. Markov Models

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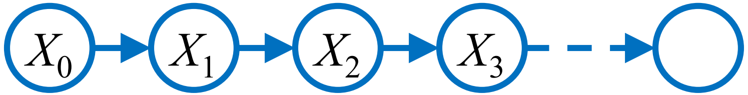
Uncertainty and Time

- Often, we want to reason about a sequence of observations where the state of the underlying system is changing
  - Speech recognition
  - Robot localization
  - User attention
  - Medical monitoring
  - Global climate

- Need to introduce time into our models

Markov Models

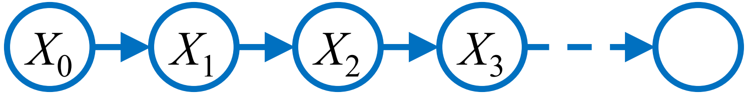
- Value of X at a given time is called the state (usually discrete, finite)



- Discrete-time model: view the problem as snapshots in time, called time slices
  - Each time slice contains a set of random variables, some observable and some not
    - We will assume the same subset of variables are observable in every time slice
- Transition model: $P(X_t \mid X_{t-1})$ how the state evolves over time
- Stationarity assumption: transition probabilities are the same at all times

Markov Models

- Markov assumption: "future is independent of the past given the present"



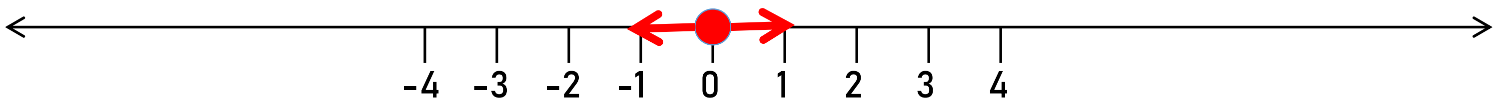
$P(X_0)$ $\qquad$ $P(X_t \mid X_{0:t-1}) = P(X_t \mid X_{t-1})$

  - X_{t+1} is independent of $X_0, \ldots, X_{t-1}$ given X_t
  - This is a first-order Markov model (a kth-order model allows dependencies on k earlier steps)
  - Higher order Markov chains can be transformed to the first order chain
  - Also called Markov chain or Markov process
- Joint distribution $P(X_0, \ldots, X_T) = P(X_0) \prod_t P(X_t \mid X_{t-1})$

Are Markov models a special case of Bayes nets?

- Yes and no!
- Yes:
  - Directed acyclic graph, joint = product of conditionals
- No:
  - Infinitely many variables (unless we truncate)
  - Repetition of transition model not part of standard Bayes net syntax
- They are “growable” Bayes nets

Example: Random walk in one dimension



- State: location on the unbounded integer line
- Initial probability: starts at 0
- Transition model: $P(X_t = k | X_{t-1} = k \pm 1) = 0.5$
- Applications: particle motion in crystals, stock prices, gambling, genetics, etc.
- Questions:
  - How far does it get as a function of t?
    - Expected distance is $O(\sqrt{t})$
  - Does it get back to 0 or can it go off for ever and not come back?
    - In 1D and 2D, returns w.p. 1; in 3D, returns w.p. 0.34053733

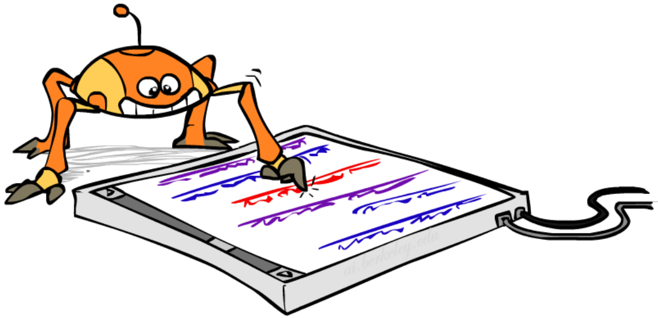
Example: n-gram models

- State: word at position t in text (can also build letter n-grams)
- Transition model (probabilities come from empirical frequencies):
  - Unigram (zero-order): $P(Word_t = i)$
    - “logical are as are confusion a may right tries agent goal the was . . .”
  - Bigram (first-order): $P(Word_t = i \mid Word_{t-1} = j)$
    - “systems are very similar computational approach would be represented . . .”
  - Trigram (second-order): $P(Word_t = i \mid Word_{t-1} = j, Word_{t-2} = k)$
    - “planning and scheduling are integrated the success of naive bayes model is . . .”
- Applications: text classification, spam detection, author identification, language classification, speech recognition

We call ourselves *Homo sapiens*—man the wise—because our **intelligence** is so important to us. For thousands of years, we have tried to understand *how we think*; that is, how a mere handful of matter can perceive, understand, predict, and manipulate a world far larger and more complicated than itself. ....

Example: Web browsing

- State: URL visited at step t
- Transition model:
  - With probability p, choose an outgoing link at random
  - With probability $(1-p)$, choose an arbitrary new page
- Question: What is the stationary distribution over pages?
  - I.e., if the process runs forever, what fraction of time does it spend in any given page?
- Application: Google page rank



Example: Weather

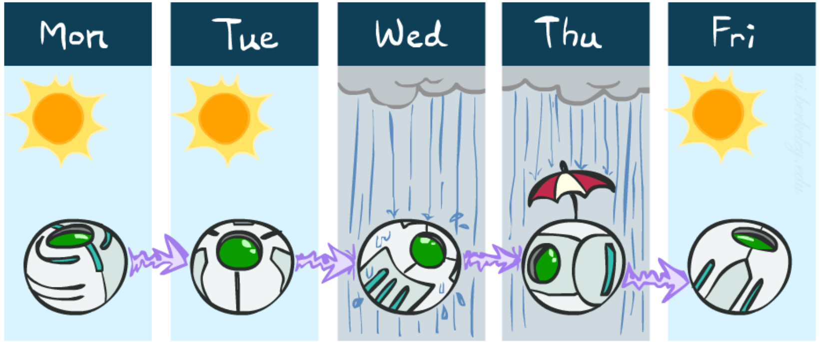
- States {rain, sun}

- Initial distribution $P(X_0)$

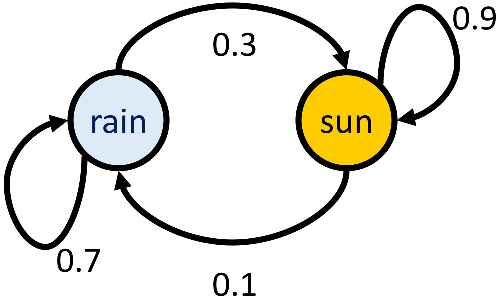
$P(X_0)$	
sun	rain
0.5	0.5

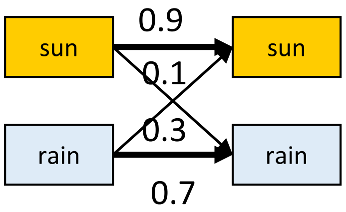
- Transition model $P(X_t \mid X_{t-1})$

X_{t-1}	$P(X_t \mid X_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7



More ways of representing the same CPT

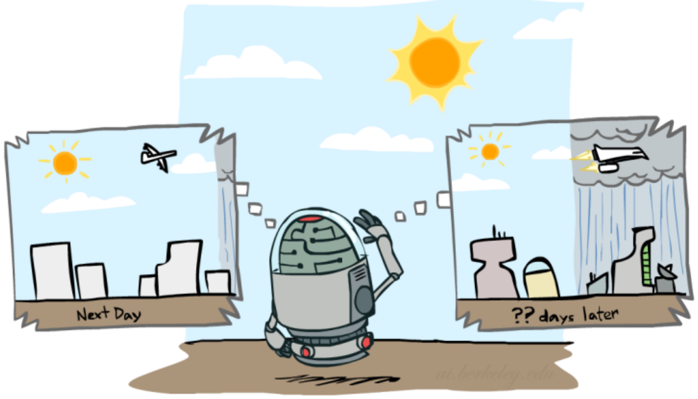




Weather prediction

- Time 0: $\langle 0.5, 0.5 \rangle$

X_{t-1}	$P(X_t \mid X_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7



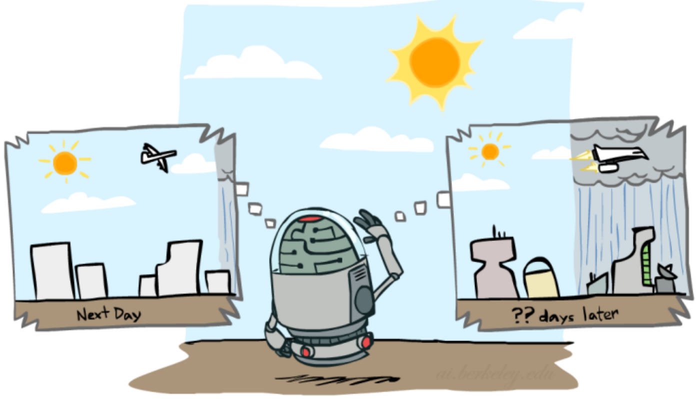
- What is the weather like at time 1?

$$
\begin{aligned}
P(X_1) &= \textstyle\sum_{x_0} P(X_1, X_0{=}x_0) \\
&= \textstyle\sum_{x_0} P(X_0{=}x_0)\, P(X_1 \mid X_0{=}x_0) \\
&= 0.5\langle 0.9, 0.1\rangle + 0.5\langle 0.3, 0.7\rangle = \langle 0.6, 0.4\rangle
\end{aligned}
$$

Weather prediction, contd.

- Time 1: $\langle 0.6, 0.4 \rangle$

X_{t-1}	$P(X_t \mid X_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7



- What is the weather like at time 2?

$$P(X_2) = \sum_{x_1} P(X_2, X_1 = x_1)$$
$$= \sum_{x_1} P(X_1 = x_1)\, P(X_2 \mid X_1 = x_1)$$
$$= 0.6\langle 0.9, 0.1\rangle + 0.4\langle 0.3, 0.7\rangle = \langle 0.66, 0.34\rangle$$

Weather prediction, contd.

- Time 2: <0.66, 0.34>

X_{t-1}	$P(X_t \mid X_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7

- What is the weather like at time 3?

$$P(X_3) = \sum_{x_2} P(X_3, X_2 = x_2)$$
$$= \sum_{x_2} P(X_2 = x_2)\, P(X_3 \mid X_2 = x_2)$$
$$= 0.66\langle 0.9, 0.1\rangle + 0.34\langle 0.3, 0.7\rangle = \langle 0.696, 0.304\rangle$$

Homework

$P(X_0)$	
sun	rain
0	1

- The influence of initial distribution gets less and less over time. The distribution much later becomes independent of the initial distribution

Forward algorithm (simple form)

Transition model

- What is the state at time t?
  - $P(X_t) = \sum_{x_{t-1}} P(X_t, X_{t-1}=x_{t-1})$
  - $\quad = \sum_{x_{t-1}} P(X_{t-1}=x_{t-1}) \, P(X_t \mid X_{t-1}=x_{t-1})$
- Iterate this update starting at $t=0$
  - This is called a recursive update: $P_t = g(P_{t-1}) = g(g(g(g(\ldots P_0))))$

And the same thing in linear algebra

- What is the weather like at time 2?
  - $P(X_2) = 0.6\langle 0.9,0.1\rangle + 0.4\langle 0.3,0.7\rangle = \langle 0.66,0.34\rangle$
- In matrix-vector form:
  - $P(X_2) = \begin{pmatrix} 0.9 & 0.3 \\ 0.1 & 0.7 \end{pmatrix} \begin{pmatrix} 0.6 \\ 0.4 \end{pmatrix} = \begin{pmatrix} 0.66 \\ 0.34 \end{pmatrix}$

X_{t-1}	$P(X_t \mid X_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7

i.e., multiply by T^T, transpose of transition matrix

Stationary Distributions

- The limiting distribution is called the stationary distribution P_∞ of the chain
- It satisfies $P_\infty = P_{\infty+1} = T^T P_\infty$
- Solving for P_∞ in the example:

$$\begin{pmatrix} 0.9 & 0.3 \\ 0.1 & 0.7 \end{pmatrix} \begin{pmatrix} p \\ 1-p \end{pmatrix} = \begin{pmatrix} p \\ 1-p \end{pmatrix}$$

$0.9p + 0.3(1-p) = p$

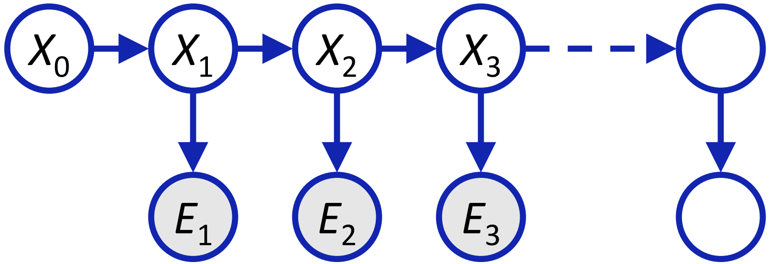
$p = 0.75$

Stationary distribution is $<0.75, 0.25>$ regardless of the starting distribution

Hidden Markov Models

Hidden Markov Models

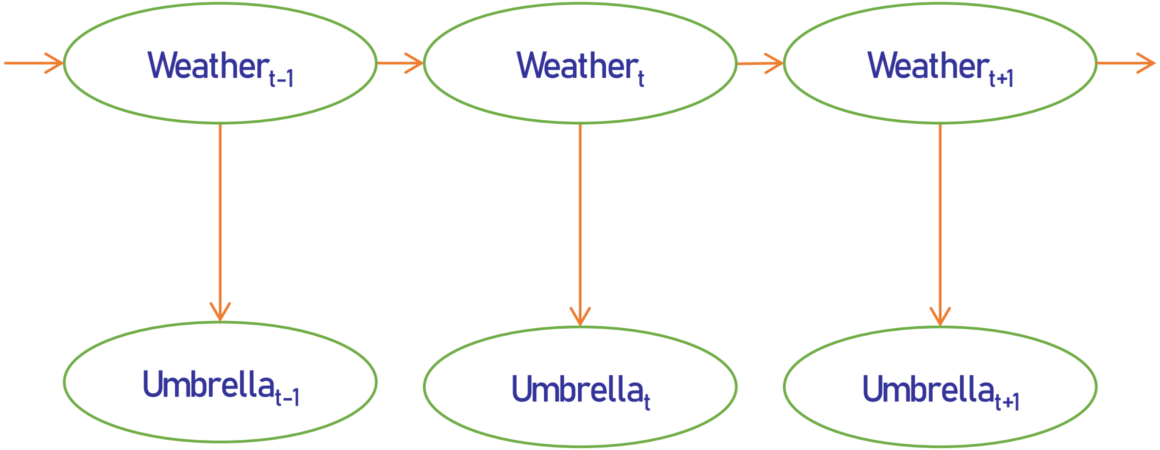
- Usually the true state is not observed directly
  - An agent maintains a belief state
- Hidden Markov models (HMMs)
  - Underlying Markov chain over belief states X
  - You observe evidence E at each time step
  - X_t is a single discrete variable; E_t may be continuous and may consist of several variables



Example: Weather HMM

- An HMM is defined by:
  - Initial distribution: $P(X_0)$
  - Transition model: $P(X_t \mid X_{t-1})$
  - Sensor model: $P(E_t \mid X_t)$

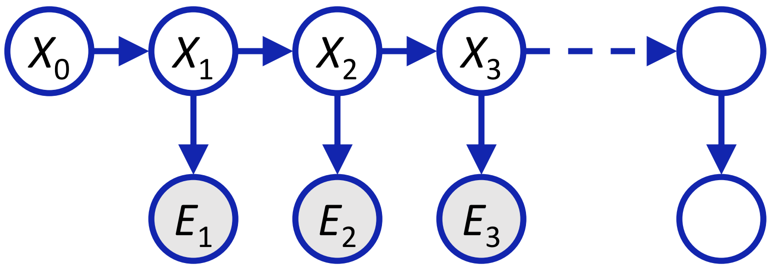
W_{t-1}	$P(W_t \mid W_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7



W_t	$P(U_t \mid W_t)$	
	true	false
sun	0.2	0.8
rain	0.9	0.1

HMM as probability model

- Joint distribution for Markov model: $P(X_{0:t}) = P(X_0) \prod_{i=1:t} P(X_i \mid X_{i-1})$
- Joint distribution for hidden Markov model:
  $P(X_{0:t}, E_{1:t}) = P(X_0) \prod_{i=1:t} P(X_i \mid X_{i-1})\, P(E_i \mid X_i)$
  - Future states are independent of the past given the present
  - Current evidence is independent of everything else given the current state
- Are evidence variables independent of each other?



Useful notation:

$X_{a:b} = X_a, X_{a+1}, \ldots, X_b$

Real HMM Examples

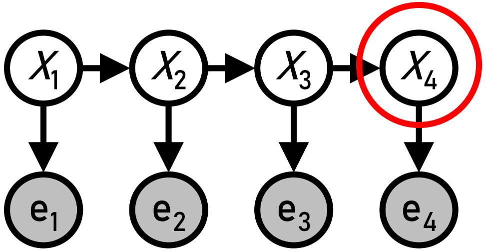
- Speech recognition HMMs:
  - Observations are acoustic signals (continuous valued)
  - States are specific positions in specific words (so, tens of thousands)
- Machine translation HMMs:
  - Observations are words (tens of thousands)
  - States are translation options
- Robot tracking:
  - Observations are range readings (continuous)
  - States are positions on a map (continuous)

Inference tasks

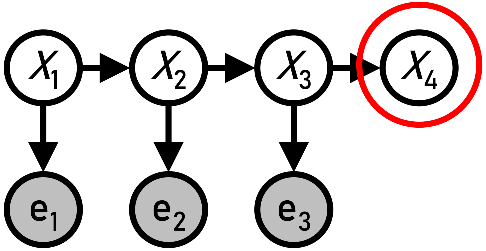
- Filtering: $P(X_t | e_{1:t})$
  - belief state—input to the decision process of a rational agent
- Prediction: $P(X_{t+k} | e_{1:t})$ for $k > 0$
  - evaluation of possible action sequences; like filtering without the evidence
- Smoothing: $P(X_k | e_{1:t})$ for $0 \le k < t$
  - better estimate of past states, essential for learning
- Most likely explanation: $\arg\max_{x_{1:t}} P(x_{1:t} \mid e_{1:t})$
  - speech recognition, decoding with a noisy channel

Inference tasks

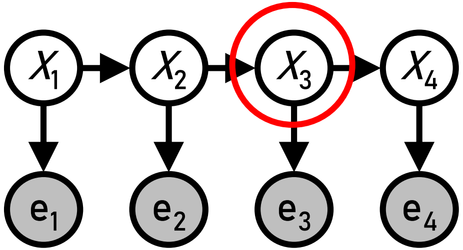
Filtering: $P(X_t|e_{1:t})$



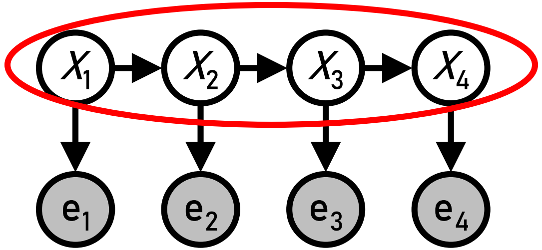
Prediction: $P(X_{t+k}|e_{1:t})$



Smoothing: $P(X_k|e_{1:t})$, $k<t$



Explanation: $P(X_{1:t}|e_{1:t})$



Filtering / Monitoring

- Filtering, or monitoring, or state estimation, is the task of maintaining the distribution $f_{1:t} = P(X_t|e_{1:t})$ over time
- We start with f_0 in an initial setting, usually uniform
- Filtering is a fundamental task in engineering and science
- The Kalman filter (continuous variables, linear dynamics, Gaussian noise) was invented in 1960 and used for trajectory estimation in the Apollo program
  - Core ideas used by Gauss for planetary observations
  - 788,000 papers on Google Scholar

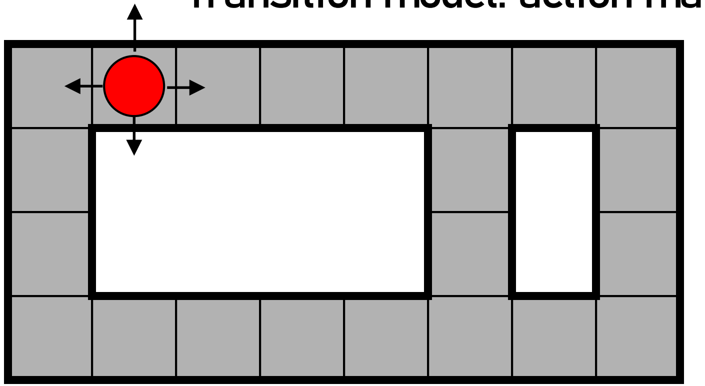
Example: Robot Localization

t=0

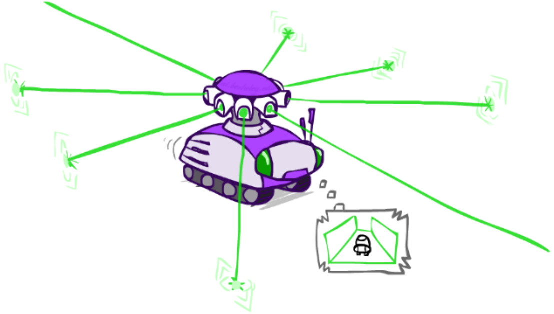
Sensor model: four bits for wall/no-wall in each direction, never more than 1 mistake

Transition model: action may fail with small prob.

Example from Michael Pfeiffer



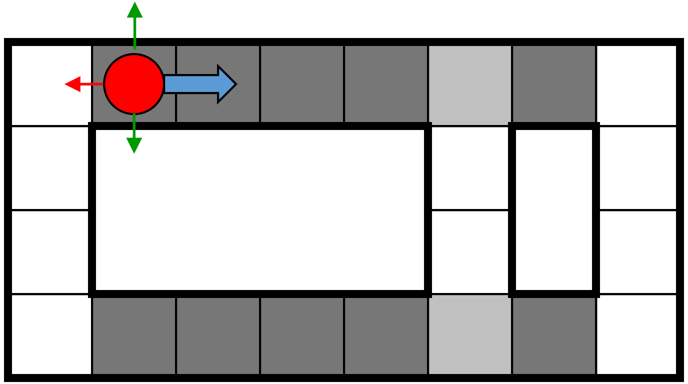
Prob 0 1

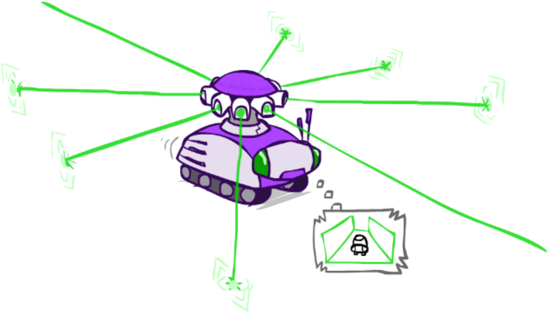


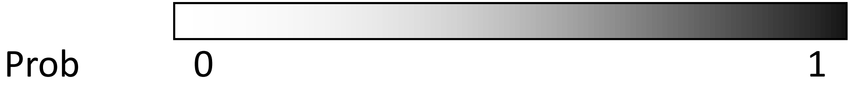
Example: Robot Localization

t=1

Lighter grey: was *possible* to get the reading, but *less likely* (required 1 mistake)

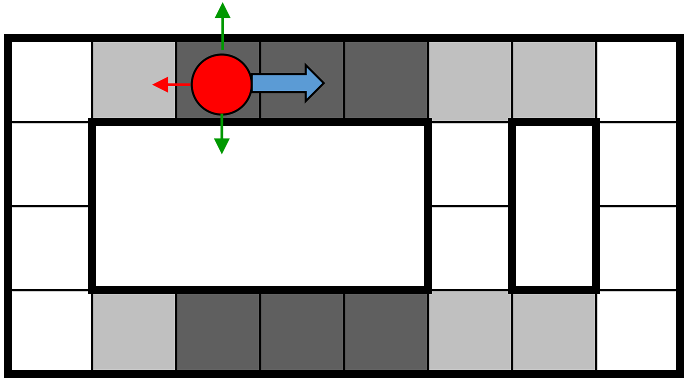


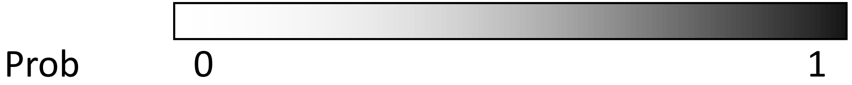


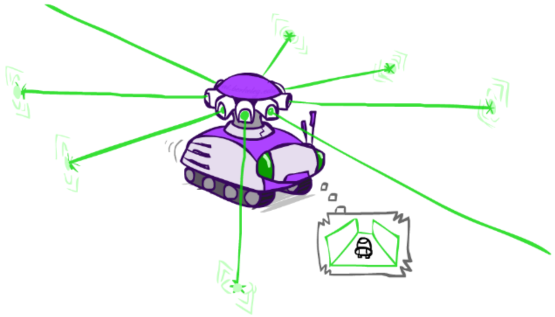


Example: Robot Localization

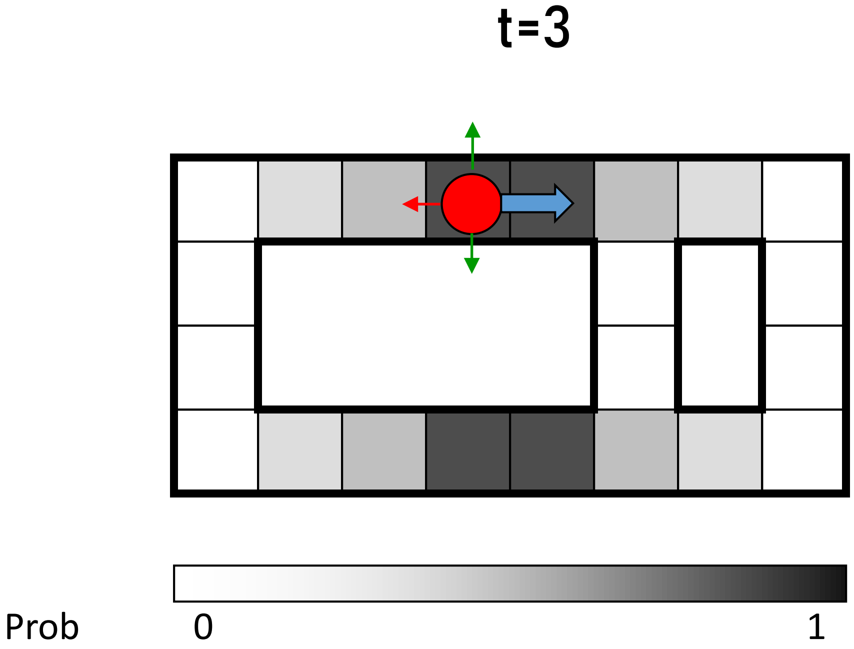
t=2

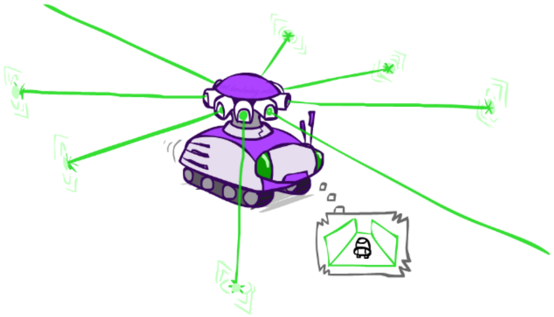






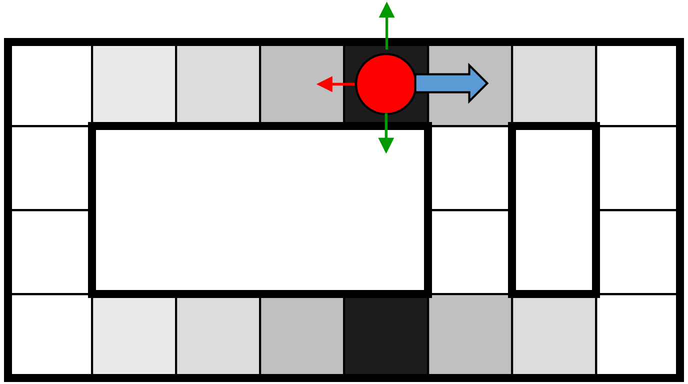
Example: Robot Localization



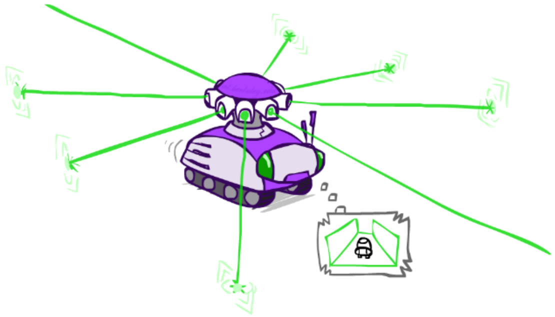


Example: Robot Localization

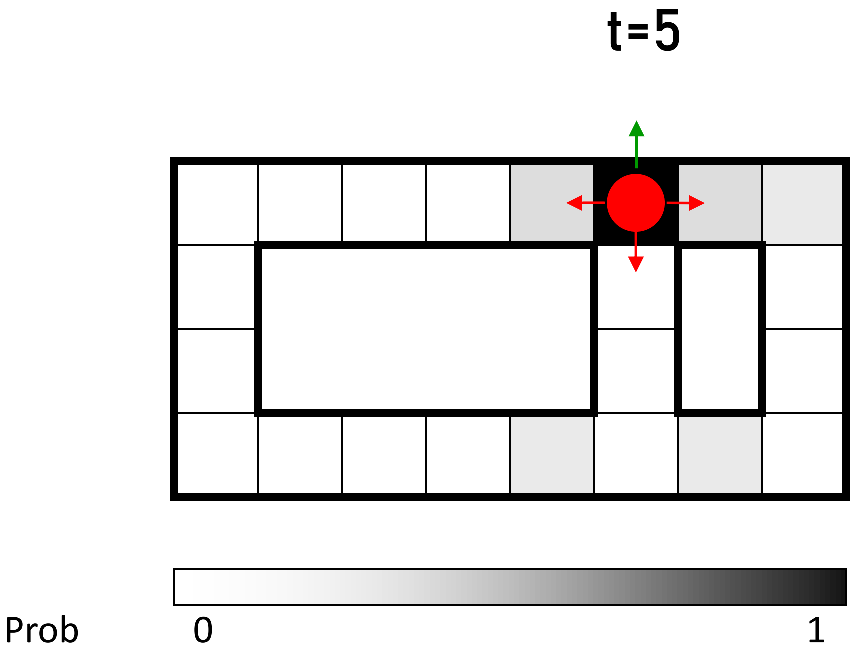
t=4

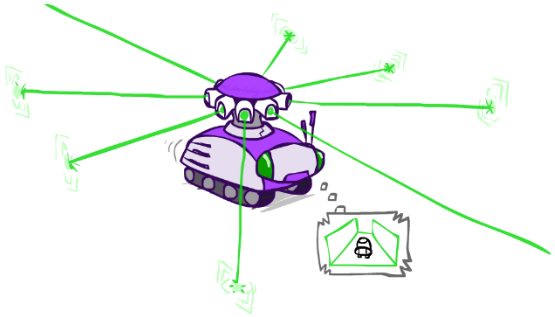


Prob 0 1



Example: Robot Localization





Filtering algorithm

- Aim: devise a recursive filtering algorithm of the form
  - $P(X_{t+1}|e_{1:t+1}) = g(e_{t+1}, P(X_t|e_{1:t}))$

- $P(X_{t+1}|e_{1:t+1}) =$

Filtering algorithm

- Aim: devise a recursive filtering algorithm of the form
  - $P(X_{t+1}|e_{1:t+1}) = f(e_{t+1}, P(X_t|e_{1:t}))$

- $P(X_{t+1}|e_{1:t+1}) = P(X_{t+1}|e_{1:t}, e_{t+1})$

Filtering algorithm

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  - $P(X_{t+1}|e_{1:t+1}) = f(e_{t+1}, P(X_t|e_{1:t}))$

- $P(X_{t+1}|e_{1:t+1}) = P(X_{t+1}|e_{1:t}, e_{t+1})$

$$= \alpha\, P(e_{t+1}|X_{t+1}, e_{1:t})\, P(X_{t+1}|\, e_{1:t})$$

Apply Bayes' rule

Filtering algorithm

- Aim: devise a recursive filtering algorithm of the form
  - $P(X_{t+1}|e_{1:t+1}) = f(e_{t+1}, P(X_t|e_{1:t}))$

- $P(X_{t+1}|e_{1:t+1}) = P(X_{t+1}|e_{1:t}, e_{t+1})$

$$= \alpha\, P(e_{t+1}|X_{t+1}, e_{1:t})\, P(X_{t+1}| e_{1:t})$$

$$= \alpha\, \underline{P(e_{t+1}|X_{t+1})}\, P(X_{t+1}| e_{1:t})$$

Apply sensor Markov conditional independence

Filtering algorithm

- Aim: devise a recursive filtering algorithm of the form
  - $P(X_{t+1}|e_{1:t+1}) = f(e_{t+1}, P(X_t|e_{1:t}))$

- $P(X_{t+1}|e_{1:t+1}) = P(X_{t+1}|e_{1:t}, e_{t+1})$

$$= \alpha\, P(e_{t+1}|X_{t+1}, e_{1:t})\, P(X_{t+1}|\, e_{1:t})$$
$$= \alpha\, P(e_{t+1}|X_{t+1})\, P(X_{t+1}|\, e_{1:t})$$
$$= \alpha\, P(e_{t+1}|X_{t+1}) \sum_{x_t} P(x_t \,|\, e_{1:t})\, P(X_{t+1}|\, x_t, e_{1:t})$$

Condition on X_t

Filtering algorithm

- Aim: devise a recursive filtering algorithm of the form
  - $P(X_{t+1}|e_{1:t+1}) = f(e_{t+1}, P(X_t|e_{1:t}))$

- $P(X_{t+1}|e_{1:t+1}) = P(X_{t+1}|e_{1:t}, e_{t+1})$

$$
\begin{aligned}
&= \alpha\, P(e_{t+1}|X_{t+1}, e_{1:t})\, P(X_{t+1}| e_{1:t}) \\
&= \alpha\, P(e_{t+1}|X_{t+1})\, P(X_{t+1}| e_{1:t}) \\
&= \alpha\, P(e_{t+1}|X_{t+1}) \sum_{x_t} P(x_t \mid e_{1:t})\, P(X_{t+1}| x_t, e_{1:t}) \\
&= \underbrace{\alpha}_{\text{Normalize}}\, \underbrace{P(e_{t+1}|X_{t+1})}_{\text{Sensor model}} \sum_{x_t} \underbrace{P(X_{t+1}| x_t)}_{\text{Transition model}}\ \ \underbrace{P(x_t \mid e_{1:t})}_{\text{Recursion}}
\end{aligned}
$$

Apply conditional independence

Filtering algorithm

- $P(X_{t+1}|e_{1:t+1}) = \underbrace{\alpha}_{\text{Normalize}} \; \underbrace{P(e_{t+1}|X_{t+1})}_{\text{Update}} \; \underbrace{\sum_{x_t} P(x_t \mid e_{1:t}) \, P(X_{t+1} \mid x_t)}_{\text{Predict}}$

- $f_{1:t+1}$ = FORWARD($f_{1:t}$, e_{t+1})
- Cost per time step: $O(|X|^2)$ where $|X|$ is the number of states
- Time and space costs are constant, independent of t
- $O(|X|^2)$ is infeasible for models with many state variables
- We get to invent really cool approximate filtering algorithms

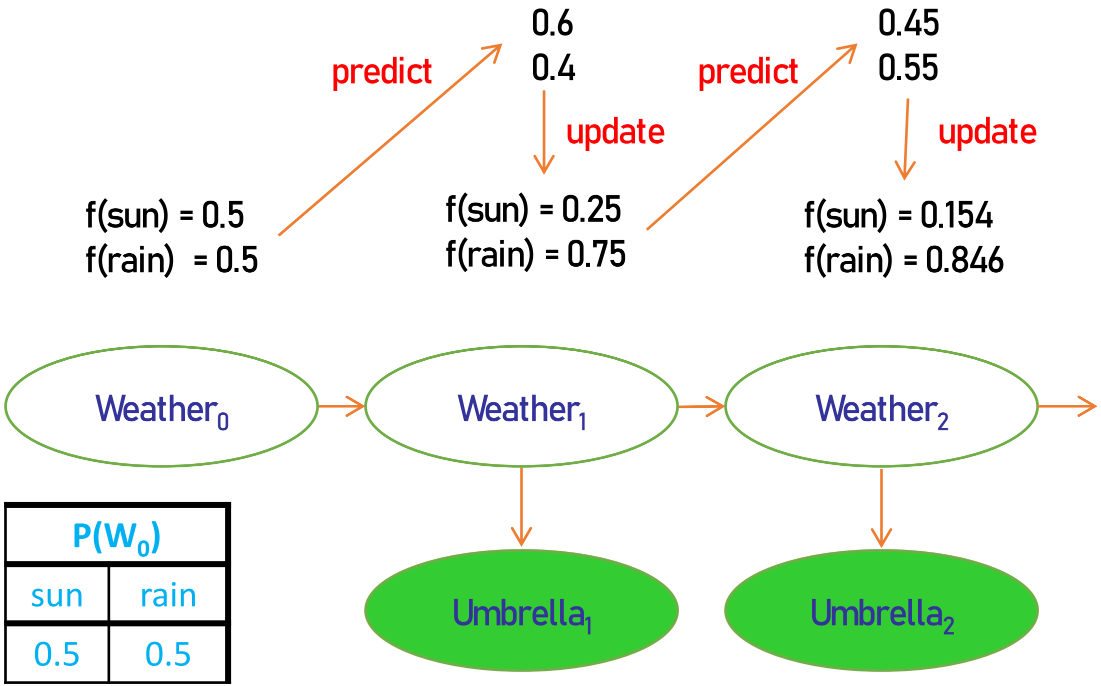
And the same thing in linear algebra

- Transition matrix T, observation matrix O_t
  - Observation matrix has state likelihoods for E_t along diagonal
  - E.g., for $U_1 = \text{true}$, $O_1 = \begin{pmatrix} 0.2 & 0 \\ 0 & 0.9 \end{pmatrix}$
- Filtering algorithm becomes
  - $f_{1:t+1} = \alpha\, O_{t+1} T^T f_{1:t}$

X_{t-1}	$P(X_t \mid X_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7

W_t	$P(U_t \mid W_t)$	
	true	false
sun	0.2	0.8
rain	0.9	0.1

Example: Weather HMM



$P(W_0)$	
sun	rain
0.5	0.5

W_{t-1}	$P(W_t \mid W_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7

W_t	$P(U_t \mid W_t)$	
	true	false
sun	0.2	0.8
rain	0.9	0.1

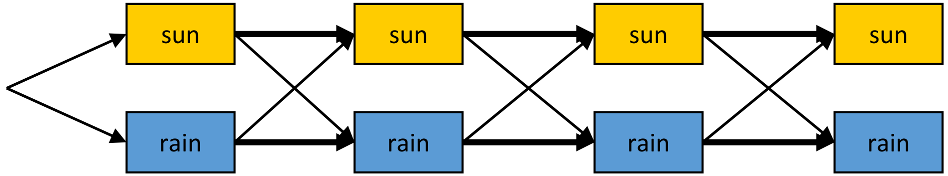
Most Likely Explanation

Inference tasks

- **Filtering**: $P(X_t|e_{1:t})$
  - belief state—input to the decision process of a rational agent
- **Prediction**: $P(X_{t+k}|e_{1:t})$ for $k > 0$
  - evaluation of possible action sequences; like filtering without the evidence
- **Smoothing**: $P(X_k|e_{1:t})$ for $0 \leq k < t$
  - better estimate of past states, essential for learning
- **Most likely explanation**: $\arg\max_{x_{1:t}} P(x_{1:t} \mid e_{1:t})$
  - speech recognition, decoding with a noisy channel

Most likely explanation = most probable path

- State trellis: graph of states and transitions over time

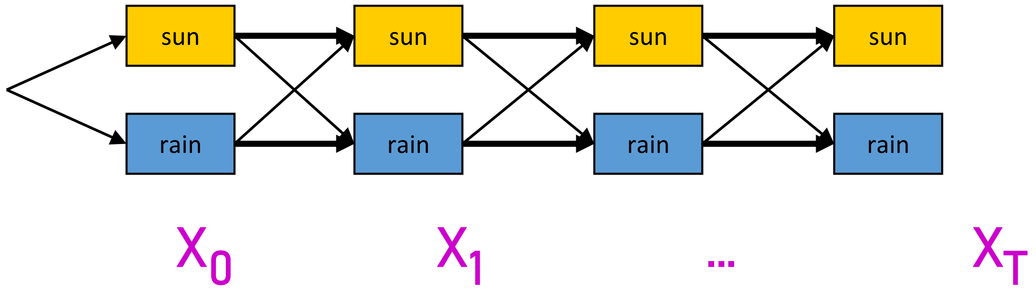


X_0 X_1 … X_T

$$\arg\max_{x_{1:t}} P(x_{1:t} \mid e_{1:t})$$
$$= \arg\max_{x_{1:t}} \alpha P(x_{1:t}, e_{1:t})$$
$$= \arg\max_{x_{1:t}} P(x_{1:t}, e_{1:t})$$
$$= \arg\max_{x_{1:t}} P(x_0) \prod_t P(x_t \mid x_{t-1}) P(e_t \mid x_t)$$

- Each arc represents some transition $x_{t-1} \rightarrow x_t$
- Each arc has weight $P(x_t \mid x_{t-1}) P(e_t \mid x_t)$
  - Arcs to initial states have weight $P(x_0)$)
- The product of weights on a path is proportional to that state sequence's probability
- Forward algorithm computes sums of paths, Viterbi algorithm computes best paths

Forward / Viterbi algorithms



Forward Algorithm (sum)

For each state at time t, keep track of the total probability of all paths to it

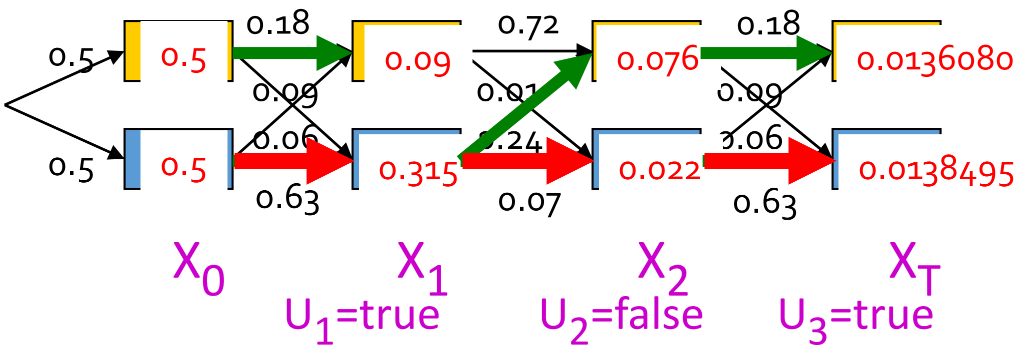
$$f_{1:t+1} = \textsc{Forward}(f_{1:t}\ ,\ e_{t+1})$$
$$= \alpha\ P(e_{t+1}|X_{t+1})\ \sum_{x_t} P(X_{t+1}|\ x_t)\ f_{1:t}$$

Viterbi Algorithm (max)

For each state at time t, keep track of the maximum probability of any path to it

$$m_{1:t+1} = \textsc{Viterbi}(m_{1:t}\ ,\ e_{t+1})$$
$$= P(e_{t+1}|X_{t+1})\ \max_{x_t} P(X_{t+1}|\ x_t)\ m_{1:t}$$

Viterbi algorithm contd.



W_{t-1}	$P(W_t \mid W_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7

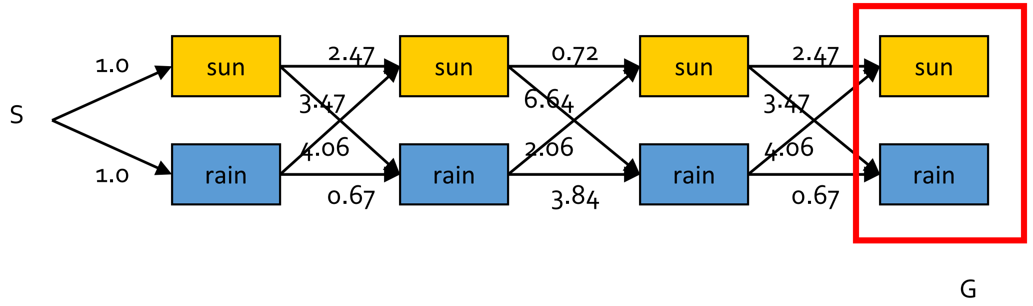
W_t	$P(U_t \mid W_t)$	
	true	false
sun	0.2	0.8
rain	0.9	0.1

Time complexity?
$O(|X|^2\ T)$

Space complexity?
$O(|X|\ T)$

Number of paths?
$O(|X|^T)$

Viterbi in negative log space



W_{t-1}	$P(W_t \mid W_{t-1})$	
	sun	rain
sun	0.9	0.1
rain	0.3	0.7

W_t	$P(U_t \mid W_t)$	
	true	false
sun	0.2	0.8
rain	0.9	0.1

argmax of product of probabilities
= argmin of sum of negative log probabilities
= minimum-cost path

Viterbi is essentially breadth-first graph search
What about A*?

Next time

- Chapter 16. Utility theory