

Parametric Models

Part III: Hidden Markov Models

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Discrete Markov Processes (Markov Chains)

- ▶ The goal is to make a sequence of decisions where a particular decision may be influenced by earlier decisions.
- ▶ Consider a system that can be described at any time as being in one of a set of N distinct states w_1, w_2, \dots, w_N .
- ▶ Let $w(t)$ denote the actual state at time t where $t = 1, 2, \dots$
- ▶ The probability of the system being in state $w(t)$ is $P(w(t)|w(t-1), \dots, w(1))$.



First-Order Markov Models

- ▶ We assume that the state $w(t)$ is conditionally independent of the previous states given the predecessor state $w(t - 1)$, i.e.,

$$P(w(t)|w(t - 1), \dots, w(1)) = P(w(t)|w(t - 1)).$$

- ▶ We also assume that the Markov Chain defined by $P(w(t)|w(t - 1))$ is time homogeneous (independent of the time t).



First-Order Markov Models

- ▶ A particular *sequence of states* of length T is denoted by

$$\mathcal{W}^T = \{w(1), w(2), \dots, w(T)\}.$$

- ▶ The model for the production of any sequence is described by the *transition probabilities*

$$a_{ij} = P(w(t) = w_j | w(t-1) = w_i)$$

where $i, j \in \{1, \dots, N\}$, $a_{ij} \geq 0$, and $\sum_{j=1}^N a_{ij} = 1, \forall i$.



First-Order Markov Models

- ▶ There is no requirement that the transition probabilities are symmetric ($a_{ij} \neq a_{ji}$, in general).
- ▶ Also, a particular state may be visited in succession ($a_{ii} \neq 0$, in general) and not every state need to be visited.
- ▶ This process is called an *observable Markov model* because the output of the process is the set of states at each instant of time, where each state corresponds to a physical (observable) event.



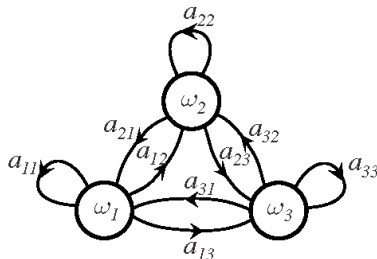
First-Order Markov Model Examples

- ▶ Consider the following 3-state first-order Markov model of the weather in Ankara:

- ▶ w_1 : rain/snow
- ▶ w_2 : cloudy
- ▶ w_3 : sunny

$$\Theta = \{a_{ij}\}$$

$$= \begin{pmatrix} 0.4 & 0.3 & 0.3 \\ 0.2 & 0.6 & 0.2 \\ 0.1 & 0.1 & 0.8 \end{pmatrix}$$



First-Order Markov Model Examples

- ▶ We can use this model to answer the following: Starting with sunny weather on day 1 (given), what is the probability that the weather for the next seven days will be “sunny-sunny-rainy-rainy-sunny-cloudy-sunny” ($\mathcal{W}^8 = \{w_3, w_3, w_3, w_1, w_1, w_3, w_2, w_3\}$)?
- ▶ Solution:

$$\begin{aligned}P(\mathcal{W}^8 | \Theta) &= P(w_3, w_3, w_3, w_1, w_1, w_3, w_2, w_3) \\&= P(w_3)P(w_3|w_3)P(w_3|w_3)P(w_1|w_3) \\&\quad P(w_1|w_1)P(w_3|w_1)P(w_2|w_3)P(w_3|w_2) \\&= P(w_3) a_{33} a_{33} a_{31} a_{11} a_{13} a_{32} a_{23} \\&= 1 \times 0.8 \times 0.8 \times 0.1 \times 0.4 \times 0.3 \times 0.1 \times 0.2 \\&= 1.536 \times 10^{-4}\end{aligned}$$



First-Order Markov Model Examples

- ▶ Consider another question: Given that the model is in a known state, what is the probability that it stays in that state for exactly d days?
- ▶ Solution:

$$\mathcal{W}^{d+1} = \{w(1) = w_i, w(2) = w_i, \dots, w(d) = w_i, w(d+1) = w_j \neq w_i\}$$

$$P(\mathcal{W}^{d+1} | \Theta, w(1) = w_i) = (a_{ii})^{d-1} (1 - a_{ii})$$

$$E[d | w_i] = \sum_{d=1}^{\infty} d (a_{ii})^{d-1} (1 - a_{ii}) = \frac{1}{1 - a_{ii}}$$

- ▶ For example, the expected number of consecutive days of sunny weather is 5, cloudy weather is 2.5, rainy weather is 1.67.



First-Order Hidden Markov Models

- ▶ We can extend this model to the case where the observation (output) of the system is a probabilistic function of the state.
- ▶ The resulting model, called a *Hidden Markov Model (HMM)*, has an underlying stochastic process that is not observable (it is hidden), but can only be observed through another set of stochastic processes that produce a sequence of observations.



First-Order Hidden Markov Models

- ▶ We denote the observation at time t as $v(t)$ and the probability of producing that observation in state $w(t)$ as $P(v(t)|w(t))$.
- ▶ There are many possible state-conditioned observation distributions.
- ▶ When the observations are discrete, the distributions

$$b_{jk} = P(v(t) = v_k | w(t) = w_j)$$

are probability mass functions where $j \in \{1, \dots, N\}$, $k \in \{1, \dots, M\}$, $b_{jk} \geq 0$, and $\sum_{k=1}^M b_{jk} = 1, \forall j$.



First-Order Hidden Markov Models

- ▶ When the observations are continuous, the distributions are typically specified using a parametric model family where the most common family is the Gaussian mixture

$$b_j(\mathbf{x}) = \sum_{k=1}^{M_j} \alpha_{jk} p(\mathbf{x} | \boldsymbol{\mu}_{jk}, \boldsymbol{\Sigma}_{jk})$$

where $\alpha_{jk} \geq 0$ and $\sum_{k=1}^{M_j} \alpha_{jk} = 1, \forall j$.

- ▶ We will restrict ourselves to discrete observations where a particular sequence of visible states of length T is denoted by

$$\mathcal{V}^T = \{v(1), v(2), \dots, v(T)\}.$$



First-Order Hidden Markov Models

- ▶ An HMM is characterized by:
 - ▶ N , the number of hidden states
 - ▶ M , the number of distinct observation symbols per state
 - ▶ $\{a_{ij}\}$, the state transition probability distribution
 - ▶ $\{b_{jk}\}$, the observation symbol probability distribution
 - ▶ $\{\pi_i = P(w(1) = w_i)\}$, the initial state distribution
 - ▶ $\Theta = (\{a_{ij}\}, \{b_{jk}\}, \{\pi_i\})$, the complete parameter set of the model



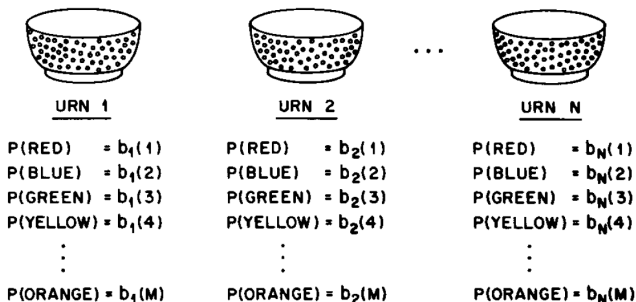
First-Order HMM Examples

- ▶ Consider the “urn and ball” example (Rabiner, 1989):
 - ▶ There are N large urns in the room.
 - ▶ Within each urn, there are a large number of colored balls where the number of distinct colors is M .
 - ▶ An initial urn is chosen according to some random process, and a ball is chosen at random from it.
 - ▶ The ball’s color is recorded as the observation and it is put back to the urn.
 - ▶ A new urn is selected according to the random selection process associated with the current urn and the ball selection process is repeated.



First-Order HMM Examples

- ▶ The simplest HMM that corresponds to the urn and ball selection process is the one where
 - ▶ each state corresponds to a specific urn,
 - ▶ a ball color probability is defined for each state.



$O = \{\text{GREEN, GREEN, BLUE, RED, YELLOW, RED, , BLUE}\}$

First-Order HMM Examples

- ▶ Let's extend the weather example.
 - ▶ Assume that you have a friend who lives in İstanbul and you talk daily about what each of you did that day.
 - ▶ Your friend has a list of activities that she/he does every day (such as playing sports, shopping, studying) and the choice of what to do is determined exclusively by the weather on a given day.
 - ▶ Assume that İstanbul has a weather state distribution similar to the one in the previous example.
 - ▶ You have no information about the weather where your friend lives, but you try to guess what it must have been like according to the activity your friend did.



First-Order HMM Examples

- ▶ This process can be modeled using an HMM where the state of the weather is the hidden variable, and the activity your friend did is the observation.
- ▶ Given the model and the activity of your friend, you can make a guess about the weather in İstanbul that day.
- ▶ For example, if your friend says that she/he played sports on the first day, went shopping on the second day, and studied on the third day of the week, you can answer questions such as:
 - ▶ What is the overall probability of this sequence of observations?
 - ▶ What is the most likely weather sequence that would explain these observations?



Applications of HMMs

- ▶ Speech recognition
- ▶ Optical character recognition
- ▶ Natural language processing (e.g., text summarization)
- ▶ Bioinformatics (e.g., protein sequence modeling)
- ▶ Video analysis (e.g., story segmentation, motion tracking)
- ▶ Robot planning (e.g., navigation)
- ▶ Economics and finance (e.g., time series, customer decisions)



Three Fundamental Problems for HMMs

- ▶ *Evaluation problem*: Given the model, compute the probability that a particular output sequence was produced by that model (solved by the forward algorithm).
- ▶ *Decoding problem*: Given the model, find the most likely sequence of hidden states which could have generated a given output sequence (solved by the Viterbi algorithm).
- ▶ *Learning problem*: Given a set of output sequences, find the most likely set of state transition and output probabilities (solved by the Baum-Welch algorithm).



HMM Evaluation Problem

- ▶ A particular *sequence of observations* of length T is denoted by

$$\mathcal{V}^T = \{v(1), v(2), \dots, v(T)\}.$$

- ▶ The probability of observing this sequence can be computed by enumerating every possible state sequence of length T as

$$\begin{aligned} P(\mathcal{V}^T | \Theta) &= \sum_{\text{all } \mathcal{W}^T} P(\mathcal{V}^T, \mathcal{W}^T | \Theta) \\ &= \sum_{\text{all } \mathcal{W}^T} P(\mathcal{V}^T | \mathcal{W}^T, \Theta) P(\mathcal{W}^T | \Theta). \end{aligned}$$



HMM Evaluation Problem

- ▶ This summation includes N^T terms in the form

$$\begin{aligned} P(\mathcal{V}^T | \mathcal{W}^T) P(\mathcal{W}^T) &= \left(\prod_{t=1}^T P(v(t) | w(t)) \right) \left(\prod_{t=1}^T P(w(t) | w(t-1)) \right) \\ &= \prod_{t=1}^T P(v(t) | w(t)) P(w(t) | w(t-1)) \end{aligned}$$

where $P(w(t) | w(t-1))$ for $t = 1$ is $P(w(1))$.

- ▶ It is unfeasible with computational complexity $O(N^T T)$.
- ▶ However, a computationally simpler algorithm called the *forward algorithm* computes $P(\mathcal{V}^T | \Theta)$ recursively.



HMM Evaluation Problem

- ▶ Define $\alpha_j(t)$ as the probability that the HMM is in state w_j at time t having generated the first t observations in \mathcal{V}^T

$$\alpha_j(t) = P(v(1), v(2), \dots, v(t), w(t) = w_j | \Theta).$$

- ▶ $\alpha_j(t), j = 1, \dots, N$ can be computed as

$$\alpha_j(t) = \begin{cases} \pi_j b_{jv(1)} & t = 1 \\ \left(\sum_{i=1}^N \alpha_i(t-1) a_{ij} \right) b_{jv(t)} & t = 2, \dots, T. \end{cases}$$

- ▶ Then, $P(\mathcal{V}^T | \Theta) = \sum_{j=1}^N \alpha_j(T).$



HMM Evaluation Problem

- ▶ Similarly, we can define a *backward algorithm* where

$$\beta_i(t) = P(v(t+1), v(t+2), \dots, v(T) | w(t) = w_i, \Theta)$$

is the probability that the HMM will generate the observations from $t+1$ to T in \mathcal{V}^T given that it is in state w_i at time t .

- ▶ $\beta_i(t), i = 1, \dots, N$ can be computed as

$$\beta_i(t) = \begin{cases} 1 & t = T \\ \sum_{j=1}^N \beta_j(t+1) a_{ij} b_{jv(t+1)} & t = T-1, \dots, 1. \end{cases}$$

- ▶ Then, $P(\mathcal{V}^T | \Theta) = \sum_{i=1}^N \beta_i(1) \pi_i b_{iv(1)}$.



HMM Evaluation Problem

- ▶ The computations of both $\alpha_j(t)$ and $\beta_i(t)$ have complexity $O(N^2T)$.
- ▶ For classification, we can compute the posterior probabilities

$$P(\Theta|\mathcal{V}^T) = \frac{P(\mathcal{V}^T|\Theta)P(\Theta)}{P(\mathcal{V}^T)}$$

where $P(\Theta)$ is the prior for a particular class, and $P(\mathcal{V}^T|\Theta)$ is computed using the forward algorithm with the HMM for that class.

- ▶ Then, we can select the class with the highest posterior.



HMM Decoding Problem

- ▶ Given a sequence of observations \mathcal{V}^T , we would like to find the most probable sequence of hidden states.
- ▶ One possible solution is to enumerate every possible hidden state sequence and calculate the probability of the observed sequence with $O(N^T T)$ complexity.
- ▶ We can also define the problem of finding the optimal state sequence as finding the one that includes the states that are individually most likely.
- ▶ This also corresponds to maximizing the expected number of correct individual states.



HMM Decoding Problem

- Define $\gamma_i(t)$ as the probability that the HMM is in state w_i at time t given the observation sequence \mathcal{V}^T

$$\begin{aligned}\gamma_i(t) &= P(w(t) = w_i | \mathcal{V}^T, \Theta) \\ &= \frac{\alpha_i(t)\beta_i(t)}{P(\mathcal{V}^T | \Theta)} = \frac{\alpha_i(t)\beta_i(t)}{\sum_{j=1}^N \alpha_j(t)\beta_j(t)}\end{aligned}$$

where $\sum_{i=1}^N \gamma_i(t) = 1$.

- Then, the individually most likely state $w(t)$ at time t becomes

$$w(t) = w_{i'} \quad \text{where } i' = \arg \max_{i=1, \dots, N} \gamma_i(t).$$



HMM Decoding Problem

- ▶ One problem is that the resulting sequence may not be consistent with the underlying model because it may include transitions with zero probability ($a_{ij} = 0$ for some i and j).
- ▶ One possible solution is the *Viterbi algorithm* that finds the single best state sequence \mathcal{W}^T by maximizing $P(\mathcal{W}^T | \mathcal{V}^T, \Theta)$ (or equivalently $P(\mathcal{W}^T, \mathcal{V}^T | \Theta)$).
- ▶ This algorithm recursively computes the state sequence with the highest probability at time t and keeps track of the states that form the sequence with the highest probability at time T (see Rabiner (1989) for details).



HMM Learning Problem

- ▶ The goal is to determine the model parameters $\{a_{ij}\}$, $\{b_{jk}\}$ and $\{\pi_i\}$ from a collection of training samples.
- ▶ Define $\xi_{ij}(t)$ as the probability that the HMM is in state w_i at time $t - 1$ and state w_j at time t given the observation sequence \mathcal{V}^T

$$\begin{aligned}\xi_{ij}(t) &= P(w(t-1) = w_i, w(t) = w_j | \mathcal{V}^T, \Theta) \\ &= \frac{\alpha_i(t-1) a_{ij} b_{jv(t)} \beta_j(t)}{P(\mathcal{V}^T | \Theta)} \\ &= \frac{\alpha_i(t-1) a_{ij} b_{jv(t)} \beta_j(t)}{\sum_{i=1}^N \sum_{j=1}^N \alpha_i(t-1) a_{ij} b_{jv(t)} \beta_j(t)}.\end{aligned}$$



HMM Learning Problem

- $\gamma_i(t)$ defined in the decoding problem and $\xi_{ij}(t)$ defined here can be related as

$$\gamma_i(t-1) = \sum_{j=1}^N \xi_{ij}(t).$$

- Then, \hat{a}_{ij} , the estimate of the probability of a transition from w_i at $t-1$ to w_j at t , can be computed as

$$\begin{aligned}\hat{a}_{ij} &= \frac{\text{expected number of transitions from } w_i \text{ to } w_j}{\text{expected total number of transitions away from } w_i} \\ &= \frac{\sum_{t=2}^T \xi_{ij}(t)}{\sum_{t=2}^T \gamma_i(t-1)}.\end{aligned}$$



HMM Learning Problem

- ▶ Similarly, \hat{b}_{jk} , the estimate of the probability of observing the symbol v_k while in state w_j , can be computed as

$$\begin{aligned}\hat{b}_{jk} &= \frac{\text{expected number of times observing symbol } v_k \text{ in state } w_j}{\text{expected total number of times in } w_j} \\ &= \frac{\sum_{t=1}^T \delta_{v(t), v_k} \gamma_j(t)}{\sum_{t=1}^T \gamma_j(t)}\end{aligned}$$

where $\delta_{v(t), v_k}$ is the Kronecker delta which is 1 only when $v(t) = v_k$.

- ▶ Finally, $\hat{\pi}_i$, the estimate for the initial state distribution, can be computed as $\hat{\pi}_i = \gamma_i(1)$ which is the expected number of times in state w_i at time $t = 1$.



HMM Learning Problem

- ▶ These are called the *Baum-Welch* equations (also called the *EM estimates for HMMs* or the *forward-backward algorithm*) that can be computed iteratively until some convergence criterion is met (e.g., sufficiently small changes in the estimated values in subsequent iterations).
- ▶ See (Bilmes, 1998) for the estimates $\hat{b}_j(\mathbf{x})$ when the observations are continuous and their distributions are modeled using Gaussian mixtures.

