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 $w_1, w_2, \ldots, w_N$.
- Let $w(t)$ denote the actual state at time $t$ where $t = 1, 2, \ldots$.
- The probability of the system being in state $w(t)$ is $P(w(t)|w(t-1), \ldots, w(1))$. 
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.,

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

- 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
  \[ \mathcal{W}^T = \{w(1), w(2), \ldots, w(T)\}. \]

- 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 $i, j \in \{1, \ldots, N\}$, $a_{ij} \geq 0$, 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 question: 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” ($W^8 = \{w_3, w_3, w_3, w_1, w_1, w_3, w_2, w_3\}$)?

- Solution:

\[
P(W^8 | \Theta) = P(w_3, w_3, w_3, w_1, w_1, w_3, w_2, w_3) \\
= P(w_3) P(w_3 | w_3) P(w_3 | w_3) P(w_1 | w_3) P(w_1 | w_1) P(w_3 | w_1) P(w_2 | w_3) P(w_3 | w_2) \\
= P(w_3) a_{33} a_{33} a_{31} a_{11} a_{13} a_{32} a_{23} \\
= 1 \times 0.8 \times 0.8 \times 0.1 \times 0.4 \times 0.3 \times 0.1 \times 0.2 \\
= 1.536 \times 10^{-4}
\]
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:

\[
\mathcal{W}^{d+1} = \{ w(1) = w_i, w(2) = w_i, \ldots, w(d) = w_i, w(d+1) = w_j \neq w_i \}
\]

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

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

- 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 $j \in \{1, \ldots, N\}$, $k \in \{1, \ldots, M\}$, $b_{jk} \geq 0$, 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

\[
b_j(x) = \sum_{k=1}^{M_j} \alpha_{jk} p(x | \mu_{jk}, \Sigma_{jk})
\]

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

\[
\mathcal{V}^T = \{v(1), v(2), \ldots, v(T)\}.
\]
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.

\[
\begin{align*}
\text{URN 1} & \quad \text{URN 2} & \quad \ldots & \quad \text{URN N} \\
\text{P(RED)} &= b_1(1) & \text{P(RED)} &= b_2(1) & \text{P(RED)} &= b_N(1) \\
\text{P(BLUE)} &= b_1(2) & \text{P(BLUE)} &= b_2(2) & \text{P(BLUE)} &= b_N(2) \\
\text{P(GREEN)} &= b_1(3) & \text{P(GREEN)} &= b_2(3) & \text{P(GREEN)} &= b_N(3) \\
\text{P(YELLOW)} &= b_1(4) & \text{P(YELLOW)} &= b_2(4) & \text{P(YELLOW)} &= b_N(4) \\
\vspace{0.5cm}
\vdots & \quad \vdots & \quad \vdots & \quad \vdots \\
\text{P(ORANGE)} &= b_1(M) & \text{P(ORANGE)} &= b_2(M) & \text{P(ORANGE)} &= b_N(M) \\
\end{align*}
\]

\[O = \{\text{GREEN, GREEN, BLUE, RED, YELLOW, RED, \ldots \ldots, BLUE}\}\]
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
  
  $$\mathcal{V}^T = \{v(1), v(2), \ldots, v(T)\}.$$

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

  $$P(\mathcal{V}^T | \Theta) = \sum_{\text{all } \mathcal{W}^T} P(\mathcal{V}^T, \mathcal{W}^T | \Theta)$$

  $$= \sum_{\text{all } \mathcal{W}^T} P(\mathcal{V}^T | \mathcal{W}^T, \Theta) P(\mathcal{W}^T | \Theta).$$
HMM Evaluation Problem

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

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

$$= \prod_{t=1}^{T} P(v(t)|w(t))P(w(t)|w(t-1))$$

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 \textit{forward algorithm} computes $P(V^T|\Theta)$ 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 $V^T$

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

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

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

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

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

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

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 $t$.

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

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

- The computations of both $\alpha_j(t)$ and $\beta_i(t)$ have complexity $O(N^2T)$. 
HMM Evaluation Problem

- For classification, we can compute the posterior probabilities

\[
P(\Theta|V^T) = \frac{P(V^T|\Theta)P(\Theta)}{P(V^T)}
\]

where \(P(\Theta)\) is the prior for a particular class, and \(P(V^T|\Theta)\) 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 $O(N^TT)$ 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 $\mathcal{V}^T$

$$\gamma_i(t) = P(w(t) = w_i | \mathcal{V}^T, \Theta)$$

$$= \frac{\alpha_i(t)\beta_i(t)}{P(\mathcal{V}^T|\Theta)} = \frac{\alpha_i(t)\beta_i(t)}{\sum_{j=1}^{N} \alpha_j(t)\beta_j(t)}$$

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

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

$$w(t) = w_{i'} \text{ where } i' = \arg\max_{i=1,...,N} \gamma_i(t).$$
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 $W^T$ by maximizing $P(W^T|V^T, \Theta)$ (or equivalently $P(W^T, V^T|\Theta)$).

• 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 \( \mathcal{V}^T \)

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

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

$$\hat{b}_{jk} = \frac{\text{expected number of times observing symbol } v_k \text{ in state } w_j}{\text{expected total number of times in } w_j}$$

$$= \frac{\sum_{t=1}^{T} \delta_{v(t),v_k} \gamma_j(t)}{\sum_{t=1}^{T} \gamma_j(t)}$$

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 $\hat{b}_j(x)$ when the observations are continuous and their distributions are modeled using Gaussian mixtures.