Hidden Markov Models
and
Gaussian Mixture Models

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## Overview

### HMMs and GMMs

- Key models and algorithms for HMM acoustic models
- Gaussians
- GMMs: Gaussian mixture models
- HMMs: Hidden Markov models
- HMM algorithms
  - Likelihood computation (forward algorithm)
  - Most probable state sequence (Viterbi algorithm)
  - Estimating the parameters (EM algorithm)
If $X$ is the sequence of acoustic feature vectors (observations) and $W$ denotes a word sequence, the most likely word sequence $W^*$ is given by

$$W^* = \text{arg max}_W P(W | X)$$

Applying Bayes’ Theorem:

$$P(W | X) = \frac{p(X \mid W) P(W)}{p(X)}$$

$$\propto p(X \mid W) P(W)$$

$$W^* = \text{arg max}_W \left( p(X \mid W) \frac{P(W)}{p(X)} \right)$$

Acoustic model

Language model

NB: $X$ is used hereafter to denote the output feature vectors from the signal analysis module rather than DFT spectrum.
Acoustic Modelling

Recorded Speech

Signal Analysis

Training Data

Hidden Markov Model

Acoustic Model

Lexicon

Language Model

Search Space

Decoded Text (Transcription)
Hierarchical modelling of speech

Generative Model

"No right"

NO

RIGHT

n

oh

r

ai

t

Utterance

Word

Subword

HMM

Acoustics
Calculation of $p(X|W)$

$X = x_1 x_2 \ldots x_n$

$p(X|\text{sayonara}) \approx p(X_1|/s/) p(X_2|/a/) p(X_3|/y/) p(X_4|/o/) p(X_5|/n/) p(X_6|/a/) p(X_7|/r/) p(X_8|/a/)$

ASR Lectures 4&5  Hidden Markov Models and Gaussian Mixture Models

NB: some conditional independency is assumed here.
How to calculate $p(X_1|/s/)$?

Assume $x_1, x_2, \ldots, x_{T_1}$ corresponds to phoneme /s/, the *conditional probability* that we observe the sequence is

$$p(X_1|/s/) = p(x_1, \ldots, x_{T_1}|/s/), \quad x_i = (x_{1i}, \ldots, x_{Di})^t \in \mathcal{R}^d$$

We know that HMM can be employed to calculate this. (*Viterbi* algorithm, *Forward / Backward* algorithm)

To grasp the idea of probability calculation, let’s consider an extremely simple case where the length of input sequence is just one ($T_1 = 1$), and the dimensionality of $x$ is one ($d = 1$), so that we don’t need HMM.

$$p(X_1|/s/) \rightarrow p(x_1|/s/)$$
How to calculate $p(X_1|/s/)$? (cont.)

$p(x|/s/) :$ conditional probability

(conditional probability density function (pdf) of $x$)

- A **Gaussian / normal distribution** function could be employed for this:

$$P(x|/s/) = \frac{1}{\sqrt{2\pi\sigma_s^2}} e^{-\frac{(x-\mu_s)^2}{2\sigma_s^2}}$$

- The function has only two parameters, $\mu_s$ and $\sigma_s^2$

- Given a set of training samples $\{x_1, \cdots, x_N\}$, we can estimate $\mu_s$ and $\sigma_s$

$$\hat{\mu}_s = \frac{1}{N} \sum_{i=1}^{N} x_i, \quad \hat{\sigma}_s^2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \hat{\mu}_s)^2$$

- For a general case where a phone lasts more than one frame, we need to employ HMM.
Acoustic Model: Continuous Density HMM

Probabilistic finite state automaton

Parameters $\lambda$:
- Transition probabilities: $a_{kj} = P(S = j \mid S = k)$
- Output probability density function: $b_j(x) = p(x \mid S = j)$

NB: Some textbooks use $Q$ or $q$ to denote the state variable $S$. $x$ corresponds to $o_t$ in Lecture slides 02.
Acoustic Model: Continuous Density HMM

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Parameters $\lambda$:
- Transition probabilities: $a_{kj} = P(S = j \mid S = k)$
- Output probability density function: $b_j(x) = p(x \mid S = j)$

NB: Some textbooks use $Q$ or $q$ to denote the state variable $S$. $x$ corresponds to $o_t$ in Lecture slides 02.
**Markov process**: The probability of a state depends only on the previous state: \( P(S(t) | S(t-1), S(t-2), \ldots, S(1)) = P(S(t) | S(t-1)) \)

A state is conditionally independent of all other states given the previous state.

**Observation independence**: The output observation \( x(t) \) depends only on the state that produced the observation:

\[
p(x(t) | S(t), S(t-1), \ldots, S(1), x(t-1), \ldots, x(1)) = p(x(t) | S(t))
\]

An acoustic observation \( x \) is conditionally independent of all other observations given the state that generated it.
Single multivariate Gaussian with mean $\mu_j$, covariance matrix $\Sigma_j$:

$$b_j(x) = p(x \mid S = j) = \mathcal{N}(x; \mu_j, \Sigma_j)$$

$M$-component Gaussian mixture model:

$$b_j(x) = p(x \mid S = j) = \sum_{m=1}^{M} c_{jm} \mathcal{N}(x; \mu_{jm}, \Sigma_{jm})$$

Neural network:

$$b_j(x) \sim P(S = j \mid x) / P(S = j) \quad \text{NB: NN outputs posterior probabilities}$$
Consider a real valued random variable $X$

- Cumulative distribution function (cdf) $F(x)$ for $X$:

$$F(x) = P(X \leq x)$$

- To obtain the probability of falling in an interval we can do the following:

$$P(a < X \leq b) = P(X \leq b) - P(X \leq a) = F(b) - F(a)$$
The rate of change of the cdf gives us the probability density function (pdf), \( p(x) \):

\[
p(x) = \frac{d}{dx} F(x) = F'(x)
\]

\[
F(x) = \int_{-\infty}^{x} p(x)dx
\]

\( p(x) \) is not the probability that \( X \) has value \( x \). But the pdf is proportional to the probability that \( X \) lies in a small interval centred on \( x \).

Notation: \( p \) for pdf, \( P \) for probability
The Gaussian distribution (univariate)

- The **Gaussian** (or **Normal**) distribution is the most common (and easily analysed) continuous distribution.
- It is also a reasonable model in many situations (the famous “bell curve”).
- If a (scalar) variable has a Gaussian distribution, then it has a probability density function with this form:

\[
p(x \mid \mu, \sigma^2) = \mathcal{N}(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left( -\frac{(x - \mu)^2}{2\sigma^2} \right)
\]

- The Gaussian is described by two parameters:
  - the mean \( \mu \) (location)
  - the variance \( \sigma^2 \) (dispersion)
Gaussians have the same shape, with the location controlled by the mean, and the spread controlled by the variance.

One-dimensional Gaussian with zero mean and unit variance ($\mu = 0, \sigma^2 = 1$):
Properties of the Gaussian distribution

\[ \mathcal{N}(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(x - \mu)^2}{2\sigma^2}\right) \]
Parameter estimation

- Estimate mean and variance parameters of a Gaussian from data \( x_1, x_2, \ldots, x_T \)
- Use the following as the estimates:

\[
\hat{\mu} = \frac{1}{T} \sum_{t=1}^{T} x_t \quad \text{(mean)}
\]

\[
\hat{\sigma}^2 = \frac{1}{T} \sum_{t=1}^{T} (x_t - \hat{\mu})^2 \quad \text{(variance)}
\]
Exercise — maximum likelihood estimation (MLE)

Consider the log likelihood of a set of $T$ training data points $\{x_1, \ldots, x_T\}$ being generated by a Gaussian with mean $\mu$ and variance $\sigma^2$:

$$
L = \ln p(\{x_1, \ldots, x_T\} | \mu, \sigma^2) = - \frac{1}{2} \sum_{t=1}^{T} \left( \frac{(x_t - \mu)^2}{\sigma^2} - \ln \sigma^2 - \ln(2\pi) \right)
$$

$$
= - \frac{1}{2\sigma^2} \sum_{t=1}^{T} (x_t - \mu)^2 - \frac{T}{2} \ln \sigma^2 - \frac{T}{2} \ln(2\pi)
$$

By maximising the the log likelihood function with respect to $\mu$ show that the maximum likelihood estimate for the mean is indeed the sample mean:

$$
\mu_{\text{ML}} = \frac{1}{T} \sum_{t=1}^{T} x_t.
$$
The multivariate Gaussian distribution

- The $D$-dimensional vector $\mathbf{x} = (x_1, \ldots, x_D)^T$ follows a multivariate Gaussian (or normal) distribution if it has a probability density function of the following form:

$$p(\mathbf{x} | \mu, \Sigma) = \frac{1}{(2\pi)^{D/2}|\Sigma|^{1/2}} \exp \left( -\frac{1}{2}(\mathbf{x} - \mu)^T \Sigma^{-1} (\mathbf{x} - \mu) \right)$$

The pdf is parameterised by the mean vector $\mu = (\mu_1, \ldots, \mu_D)^T$ and the covariance matrix $\Sigma = \begin{pmatrix} \sigma_{11} & \cdots & \sigma_{1D} \\ \vdots & \ddots & \vdots \\ \sigma_{D1} & \cdots & \sigma_{DD} \end{pmatrix}$.

- The 1-dimensional Gaussian is a special case of this pdf.
- The argument to the exponential $0.5(\mathbf{x} - \mu)^T \Sigma^{-1} (\mathbf{x} - \mu)$ is referred to as a quadratic form.
The mean vector $\mu$ is the expectation of $x$:

$$\mu = E[x]$$

The covariance matrix $\Sigma$ is the expectation of the deviation of $x$ from the mean:

$$\Sigma = E[(x - \mu)(x - \mu)^T]$$

$\Sigma$ is a $D \times D$ symmetric matrix:

$$\sigma_{ij} = E[(x_i - \mu_i)(x_j - \mu_j)] = E[(x_j - \mu_j)(x_i - \mu_i)] = \sigma_{ji}$$

The sign of the covariance helps to determine the relationship between two components:

- If $x_j$ is large when $x_i$ is large, then $(x_i - \mu_i)(x_j - \mu_j)$ will tend to be positive;
- If $x_j$ is small when $x_i$ is large, then $(x_i - \mu_i)(x_j - \mu_j)$ will tend to be negative.
Spherical Gaussian

\[
\mu = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \Sigma = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \rho_{12} = 0
\]

NB: Correlation coefficient

\[
\rho_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii} \sigma_{jj}}} \quad (-1 \leq \rho_{ij} \leq 1)
\]
Diagonal Covariance Gaussian

\[ \mu = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \]

\[ \Sigma = \begin{pmatrix} 1 & 0 \\ 0 & 4 \end{pmatrix} \]

\[ \rho_{12} = 0 \]

NB: Correlation coefficient \( \rho_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii} \sigma_{jj}}} \) \((-1 \leq \rho_{ij} \leq 1)\)
\[ \mu = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \Sigma = \begin{pmatrix} 1 & -1 \\ -1 & 4 \end{pmatrix} \quad \rho_{12} = -0.5 \]

NB: Correlation coefficient \[ \rho_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii} \sigma_{jj}}} \quad (-1 \leq \rho_{ij} \leq 1) \]
Parameter estimation of a multivariate Gaussian distribution

- It is possible to show that the mean vector $\hat{\mu}$ and covariance matrix $\hat{\Sigma}$ that maximise the likelihood of the training data are given by:

$$\hat{\mu} = \frac{1}{T} \sum_{t=1}^{T} x_t$$

$$\hat{\Sigma} = \frac{1}{T} \sum_{t=1}^{T} (x_t - \hat{\mu})(x_t - \hat{\mu})^T$$

where $x_t = (x_{t1}, \ldots, x_{tD})^T$.

NB: $T$ denotes either the number of samples or vector transpose depending on context.
Example data
Maximum likelihood fit to a Gaussian
Data in clusters (example 1)

\[ \mu_1 = (0, 0)^T \quad \mu_2 = (1, 1)^T \quad \Sigma_1 = \Sigma_2 = 0.2 \mathbf{I} \]
Example 1 fit by a Gaussian

\[\begin{align*}
\mu_1 &= (0, 0)^T \\
\mu_2 &= (1, 1)^T \\
\Sigma_1 &= \Sigma_2 = 0.2 \mathbf{I}
\end{align*}\]
k-means clustering

- k-means is an automatic procedure for clustering unlabelled data
- Requires a prespecified number of clusters
- Clustering algorithm chooses a set of clusters with the minimum within-cluster variance
- Guaranteed to converge (eventually)
- Clustering solution is dependent on the initialisation
k-means example: data set
k-means example: initialisation
k-means example: iteration 1 (assign points to clusters)
k-means example: iteration 1 (recompute centres)
k-means example: iteration 2 (assign points to clusters)
k-means example: iteration 2 (recompute centres)
k-means example: iteration 3 (assign points to clusters)

No changes, so converged
A more flexible form of density estimation is made up of a linear combination of component densities:

\[ p(x) = \sum_{m=1}^{M} P(m)p(x|m) \]

This is called a mixture model or a mixture density

- \( p(x|m) \): component densities
- \( P(m) \): mixing parameters

Generative model:

1. Choose a mixture component based on \( P(m) \)
2. Generate a data point \( x \) from the chosen component using \( p(x|m) \)
The most important mixture model is the **Gaussian Mixture Model** (GMM), where the component densities are Gaussians.

Consider a GMM, where each component Gaussian \( \mathcal{N}(x; \mu_m, \Sigma_m) \) has mean \( \mu_m \) and a spherical covariance \( \Sigma_m = \sigma_m^2 I \)

\[
p(x) = \sum_{m=1}^{M} P(m) p(x | m) = \sum_{m=1}^{M} P(m) \mathcal{N}(x; \mu_m, \sigma_m^2 I)
\]

![Diagram](diagram.png)
GMM Parameter estimation when we know which component generated the data

- Define the indicator variable $z_{mt} = 1$ if component $m$ generated data point $x_t$ (and 0 otherwise)
- If $z_{mt}$ wasn’t hidden then we could count the number of observed data points generated by $m$:
  \[ N_m = \sum_{t=1}^{T} z_{mt} \]
  
- And estimate the mean, variance and mixing parameters as:
  \[
  \hat{\mu}_m = \frac{\sum_t z_{mt} x_t}{N_m} \\
  \hat{\sigma}^2_m = \frac{\sum_t z_{mt} \| x_t - \hat{\mu}_m \|^2}{N_m} \\
  \hat{P}(m) = \frac{1}{T} \sum_t z_{mt} = \frac{N_m}{T}
  \]
GMM Parameter estimation when we don’t know which component generated the data

- **Problem:** we don’t know $z_{mt}$ - which mixture component a data point comes from...
- Idea: use the posterior probability $P(m|x)$, which gives the probability that component $m$ was responsible for generating data point $x$.

$$P(m|x) = \frac{p(x|m)P(m)}{p(x)} = \frac{p(x|m)P(m)}{\sum_{m'=1}^{M} p(x|m')P(m')}$$

- The $P(m|x)$s are called the *component occupation probabilities* (or sometimes called the *responsibilities*).
- Since they are posterior probabilities:

$$\sum_{m=1}^{M} P(m|x) = 1$$
Estimate “soft counts” based on the component occupation probabilities $P(m \mid x_t)$:

$$N_m^* = \sum_{t=1}^{T} P(m \mid x_t)$$

We can imagine assigning data points to component $m$ weighted by the component occupation probability $P(m \mid x_t)$.

So we could imagine estimating the mean, variance and prior probabilities as:

$$\hat{\mu}_m = \frac{\sum_t P(m \mid x_t)x_t}{\sum_t P(m \mid x_t)} = \frac{\sum_t P(m \mid x_t)x_t}{N_m^*}$$

$$\hat{\sigma}_m^2 = \frac{\sum_t P(m \mid x_t)\|x_t - \hat{\mu}_m\|^2}{\sum_t P(m \mid x_t)} = \frac{\sum_t P(m \mid x_t)\|x_t - \hat{\mu}_m\|^2}{N_m^*}$$

$$\hat{P}(m) = \frac{1}{T} \sum_t P(m \mid x_t) = \frac{N_m^*}{T}$$
### EM algorithm

- **Problem!** Recall that:

\[ P(m|x) = \frac{p(x|m)P(m)}{p(x)} = \frac{p(x|m)P(m)}{\sum_{m'=1}^{M} p(x|m')P(m')} \]

We need to know \( p(x|m) \) and \( P(m) \) to estimate the parameters of \( P(m|x) \), and to estimate \( P(m) \)....

- **Solution:** an iterative algorithm where each iteration has two parts:
  - Compute the component occupation probabilities \( P(m|x) \) using the current estimates of the GMM parameters (means, variances, mixing parameters) (E-step)
  - Computer the GMM parameters using the current estimates of the component occupation probabilities (M-step)

Starting from some initialisation (e.g. using k-means for the means) these steps are alternated until convergence

- This is called the **EM Algorithm** and can be shown to maximise the likelihood. (NB: local maximum rather than global)
The likelihood of a data set \( \mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_T\} \) is given by:
\[
\mathcal{L} = \prod_{t=1}^{T} p(\mathbf{x}_t) = \prod_{t=1}^{T} \sum_{m=1}^{M} p(\mathbf{x}_t | m) P(m)
\]

We can regard the negative log likelihood as an error function:

Considering the derivatives of \( E \) with respect to the parameters, gives expressions like the previous slide.
Example 1 fit using a GMM

Fitted with a two component GMM using EM
Peakily distributed data (Example 2)

\[ \mu_1 = \mu_2 = [0 \quad 0]^T \quad \Sigma_1 = 0.1I \quad \Sigma_2 = 2I \]
Example 2 fit by a Gaussian

\[ \mu_1 = \mu_2 = [0 \quad 0]^T \quad \Sigma_1 = 0.1I \quad \Sigma_2 = 2I \]
Example 2 fit by a GMM

Fitted with a two component GMM using EM
Example 2: component Gaussians

\[ P(x | m=1) \]

\[ P(x | m=2) \]
Comments on GMMs

- GMMs trained using the EM algorithm are able to self-organise to fit a data set.
- Individual components take responsibility for parts of the data set (probabilistically).
- Soft assignment to components not hard assignment — “soft clustering”.
- GMMs scale very well, e.g.: large speech recognition systems can have 30,000 GMMs, each with 32 components: sometimes 1 million Gaussian components!! And the parameters all estimated from (a lot of) data by EM.
Output distribution:

- Single multivariate Gaussian with mean $\mu_j$, covariance matrix $\Sigma_j$:

  $$b_j(x) = p(x \mid S = j) = \mathcal{N}(x; \mu_j, \Sigma_j)$$

- $M$-component Gaussian mixture model:

  $$b_j(x) = p(x \mid S = j) = \sum_{m=1}^{M} c_{jm} \mathcal{N}(x; \mu_{jm}, \Sigma_{jm})$$
The three problems of HMMs

Working with HMMs requires the solution of three problems:

1. **Likelihood** Determine the overall likelihood of an observation sequence \( X = (x_1, \ldots, x_t, \ldots, x_T) \) being generated by an HMM.

2. **Decoding** Given an observation sequence and an HMM, determine the most probable hidden state sequence.

3. **Training** Given an observation sequence and an HMM, learn the best HMM parameters \( \lambda = \{\{a_{jk}\}, \{b_j()\}\} \)
1. Likelihood: how to calculate?

\[ p(\mathbf{X}, \text{path}_\ell \mid \lambda) = p(\mathbf{X} \mid \text{path}_\ell, \lambda)P(\text{path}_\ell \mid \lambda) \]
\[ = p(\mathbf{X} \mid s_0s_1s_1s_2s_2s_3s_3s_4, \lambda)P(s_0s_1s_1s_2s_2s_3s_3s_4 \mid \lambda) \]
\[ = b_1(x_1)b_1(x_2)b_1(x_3)b_2(x_4)b_2(x_5)b_3(x_6)b_3(x_7)a_{01}a_{11}a_{11}a_{12}a_{22}a_{23}a_{33}a_{34} \]

\[ p(\mathbf{X} \mid \lambda) = \sum_{\{\text{path}_\ell\}} p(\mathbf{X}, \text{path}_\ell \mid \lambda) \approx \max_{\text{path}_\ell} p(\mathbf{X}, \text{path}_\ell \mid \lambda) \]

forward(backward) algorithm \quad Viterbi algorithm
Trellis for /k ae t/

\[
\begin{array}{cccccccccccccccc}
S_0 & S_1 & S_2 & S_3 \\
/\text{k}/ \quad /\text{ae}/ \quad /\text{t}/ \quad & & & & \\
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 & 18 & 19 \\
\end{array}
\]
1. Likelihood: The Forward algorithm

- Goal: determine $p(\mathbf{X} | \lambda)$
- Sum over all possible state sequences $s_1 s_2 \ldots s_T$ that could result in the observation sequence $\mathbf{X}$
- Rather than enumerating each sequence, compute the probabilities recursively (exploiting the Markov assumption)
- How many paths calculations in $p(\mathbf{X} | \lambda)$?

$$\sim \underbrace{N \times N \times \cdots N}_{T \text{ times}} = N^T$$

$N$: number of HMM states

$T$: length of observation

- e.g. $N^T \approx 10^{10}$ for $N=3$, $T=20$

- Computation complexity of multiplication: $O(2TN^T)$
- The Forward algorithm reduces this to $O(TN^2)$
Visualise the problem as a *state-time trellis*
1. Likelihood: The Forward algorithm

- **Goal:** determine $p(X | \lambda)$
- **Sum over all possible state sequences** $s_1s_2\ldots s_T$ that could result in the observation sequence $X$
- Rather than enumerating each sequence, compute the probabilities recursively (exploiting the Markov assumption)
- **Forward probability**, $\alpha_t(j)$: the probability of observing the observation sequence $x_1\ldots x_t$ and being in state $j$ at time $t$:

$$\alpha_t(j) = p(x_1, \ldots, x_t, S(t)=j | \lambda)$$
1. Likelihood: The Forward recursion

- **Initialisation**

  \[ \alpha_0(s_I) = 1 \]
  \[ \alpha_0(j) = 0 \quad \text{if} \quad j \neq s_I \]

- **Recursion**

  \[ \alpha_t(j) = \sum_{i=1}^{N} \alpha_{t-1}(i) a_{ij} b_j(x_t) \quad 1 \leq j \leq N, 1 \leq t \leq T \]

- **Termination**

  \[ p(X | \lambda) = \alpha_T(s_E) = \sum_{i=1}^{N} \alpha_T(i) a_{iE} \]

  \( s_I \): initial state, \( s_E \): final state
1. Likelihood: Forward Recursion

\[ \alpha_t(j) = p(x_1, \ldots, x_t, S(t)=j | \lambda) = \sum_{i=1}^{N} \alpha_{t-1}(i) a_{ij} b_j(x_t) \]
Viterbi approximation

- Instead of summing over all possible state sequences, just consider the most likely.

- Achieve this by changing the summation to a maximisation in the recursion:

\[ V_t(j) = \max_i V_{t-1}(i)a_{ij}b_j(x_t) \]

- Changing the recursion in this way gives the likelihood of the most probable path.

- We need to keep track of the states that make up this path by keeping a sequence of \textit{backpointers} to enable a Viterbi \textit{backtrace}: the backpointer for each state at each time indicates the previous state on the most probable path.
Viterbi Recursion

\[ V_t(j) = \max_i V_{t-1}(i) a_{ij} b_j(x_t) \]

Likelihood of the most probable path

\( V_{t-1}(i) \quad a_{ij} \quad V_{t-1}(j) \quad a_{kj} \quad \max \quad V_{t}(j) \)

\( i \quad j \quad k \)

\( a_{ij} \quad a_{jj} \quad a_{kj} \)
Viterbi Recursion

Backpointers to the previous state on the most probable path

\[ V_{t-1}(i) \]
\[ V_{t-1}(j) \]
\[ V_{t-1}(k) \]

\[ a_{ij} \]
\[ a_{jj} \]
\[ a_{kj} \]

\[ b_{t}(j) = i \]
2. Decoding: The Viterbi algorithm

- **Initialisation**
  
  \[
  V_0(i) = 1 \\
  V_0(j) = 0 \text{ if } j \neq i \\
  b_{t_0}(j) = 0
  \]

- **Recursion**
  
  \[
  V_t(j) = \max_{i=1}^{N} V_{t-1}(i) a_{ij} b_j(x_t) \\
  b_{t_t}(j) = \arg \max_{i=1}^{N} V_{t-1}(i) a_{ij} b_j(x_t)
  \]

- **Termination**
  
  \[
  P^* = V_T(s_E) = \max_{i=1}^{N} V_T(i) a_{iE} \\
  s_T^* = b_{T_t}(q_E) = \arg \max_{i=1}^{N} V_T(i) a_{iE}
  \]
Backtrace to find the state sequence of the most probable path

\[ V(i) \]

\[ V(t-1)(i) \]

\[ V(t-1)(j) \]

\[ V(t-1)(k) \]

\[ bt_{i+1}(k) = i \]

\[ bt_t(i) = j \]
3. Training: Forward-Backward algorithm

- Goal: Efficiently estimate the parameters of an HMM $\lambda$ from an observation sequence
- Assume single Gaussian output probability distribution

$$b_j(x) = p(x | j) = \mathcal{N}(x; \mu_j, \Sigma_j)$$

- Parameters $\lambda$:
  - Transition probabilities $a_{ij}$:
    $$\sum_j a_{ij} = 1$$
  - Gaussian parameters for state $j$: mean vector $\mu_j$; covariance matrix $\Sigma_j$
If we knew the state-time alignment, then each observation feature vector could be assigned to a specific state.

A state-time alignment can be obtained using the most probable path obtained by Viterbi decoding.

Maximum likelihood estimate of $a_{ij}$, if $C(i \rightarrow j)$ is the count of transitions from $i$ to $j$:

$$
\hat{a}_{ij} = \frac{C(i \rightarrow j)}{\sum_k C(i \rightarrow k)}
$$

Likewise if $Z_j$ is the set of observed acoustic feature vectors assigned to state $j$, we can use the standard maximum likelihood estimates for the mean and the covariance:

$$
\hat{\mu}_j = \frac{\sum_{x \in Z_j} x}{|Z_j|}
$$

$$
\hat{\Sigma}_j = \frac{\sum_{x \in Z_j} (x - \hat{\mu}_j)(x - \hat{\mu}_j)^T}{|Z_j|}
$$
EM Algorithm

- Viterbi training is an approximation—we would like to consider all possible paths.
- In this case rather than having a hard state-time alignment we estimate a probability.
- **State occupation probability**: The probability $\gamma_t(j)$ of occupying state $j$ at time $t$ given the sequence of observations.
- Compare with component occupation probability in a GMM.
- We can use this for an iterative algorithm for HMM training: the EM algorithm (whose adaption to HMM is called 'Baum-Welch algorithm').
- Each iteration has two steps:
  - **E-step** estimate the state occupation probabilities (Expectation).
  - **M-step** re-estimate the HMM parameters based on the estimated state occupation probabilities (Maximisation).
To estimate the state occupation probabilities it is useful to define (recursively) another set of probabilities—the Backward probabilities

\[ \beta_t(j) = p(x_{t+1}, \ldots, x_T \mid S(t) = j, \lambda) \]

The probability of future observations given a the HMM is in state \( j \) at time \( t \)

- These can be recursively computed (going backwards in time)
  - Initialisation
    \[ \beta_T(i) = a_{iE} \]
  - Recursion
    \[ \beta_t(i) = \sum_{j=1}^{N} a_{ij} b_j(x_{t+1}) \beta_{t+1}(j) \quad \text{for} \quad t = T-1, \ldots, 1 \]
  - Termination
    \[ p(X \mid \lambda) = \beta_0(1) = \sum_{j=1}^{N} a_{1j} b_j(x_1) \beta_1(j) = \alpha_T(s_E) \]
$\beta_t(j) = p(x_{t+1}, \ldots, x_T | S(t) = j, \lambda) = \sum_{j=1}^{N} a_{ij} b_j(x_{t+1}) \beta_{t+1}(j)$
The **state occupation probability** $\gamma_t(j)$ is the probability of occupying state $j$ at time $t$ given the sequence of observations.

Express in terms of the forward and backward probabilities:

$$
\gamma_t(j) = P(S(t) = j \mid X, \lambda) = \frac{1}{\alpha_T(s_E)} \alpha_t(j) \beta_t(j)
$$

recalling that $p(X \mid \lambda) = \alpha_T(s_E)$

Since

$$
\alpha_t(j) \beta_t(j) = p(x_1, \ldots, x_t, S(t) = j \mid \lambda) \\
p(x_{t+1}, \ldots, x_T \mid S(t) = j, \lambda) \\
= p(x_1, \ldots, x_t, x_{t+1}, \ldots, x_T, S(t) = j \mid \lambda) \\
= p(X, S(t) = j \mid \lambda)
$$

$$
P(S(t) = j \mid X, \lambda) = \frac{p(X, S(t) = j \mid \lambda)}{p(X \mid \lambda)}
$$
Re-estimation of Gaussian parameters

- The sum of state occupation probabilities through time for a state, may be regarded as a “soft” count.
- We can use this “soft” alignment to re-estimate the HMM parameters:

\[
\hat{\mu}_j = \frac{\sum_{t=1}^{T} \gamma_t(j) x_t}{\sum_{t=1}^{T} \gamma_t(j)}
\]

\[
\hat{\Sigma}_j = \frac{\sum_{t=1}^{T} \gamma_t(j)(x_t - \hat{\mu}_j)(x_t - \hat{\mu}_j)^T}{\sum_{t=1}^{T} \gamma_t(j)}
\]
Re-estimation of transition probabilities

- Similarly to the state occupation probability, we can estimate $\xi_t(i, j)$, the probability of being in $i$ at time $t$ and $j$ at $t + 1$, given the observations:

\[
\xi_t(i, j) = P(S(t) = i, S(t+1) = j | X, \lambda) = \frac{p(S(t) = i, S(t+1) = j, X | \lambda)}{p(X | \lambda)} = \frac{\alpha_t(i) a_{ij} b_j(x_{t+1}) \beta_{t+1}(j)}{\alpha_T(s_E)}
\]

- We can use this to re-estimate the transition probabilities

\[
\hat{a}_{ij} = \frac{\sum_{t=1}^{T} \xi_t(i, j)}{\sum_{k=1}^{N} \sum_{t=1}^{T} \xi_t(i, k)}
\]
Iterative estimation of HMM parameters using the EM algorithm. At each iteration

**E step** For all time-state pairs

1. Recursively compute the forward probabilities $\alpha_t(j)$ and backward probabilities $\beta_t(j)$
2. Compute the state occupation probabilities $\gamma_t(j)$ and $\xi_t(i, j)$

**M step** Based on the estimated state occupation probabilities re-estimate the HMM parameters: mean vectors $\mu_j$, covariance matrices $\Sigma_j$ and transition probabilities $a_{ij}$

The application of the EM algorithm to HMM training is sometimes called the Forward-Backward algorithm or Baum-Welch algorithm
Extension to a corpus of utterances

- We usually train from a large corpus of $R$ utterances.
- If $x^r_t$ is the $t$ th frame of the $r$ th utterance $X^r$ then we can compute the probabilities $\alpha^r_t(j)$, $\beta^r_t(j)$, $\gamma^r_t(j)$ and $\xi^r_t(i, j)$ as before.
- The re-estimates are as before, except we must sum over the $R$ utterances, eg:

$$
\hat{\mu}_j = \frac{\sum_{r=1}^{R} \sum_{t=1}^{T} \gamma^r_t(j) x^r_t}{\sum_{r=1}^{R} \sum_{t=1}^{T} \gamma^r_t(j)}
$$

- In addition, we usually employ “embedded training”, in which fine tuning of phone labelling with “forced Viterbi alignment” or forced alignment is involved. (For details see Section 9.7 in Jurafsky and Martin’s SLP)
The assumption of a Gaussian distribution at each state is very strong; in practice the acoustic feature vectors associated with a state may be strongly non-Gaussian.

In this case an $M$-component Gaussian mixture model is an appropriate density function:

$$b_j(x) = p(x | S = j) = \sum_{m=1}^{M} c_{jm} \mathcal{N}(x; \mu_{jm}, \Sigma_{jm})$$

Given enough components, this family of functions can model any distribution.

Train using the EM algorithm, in which the component estimation probabilities are estimated in the E-step.
Rather than estimating the state-time alignment, we estimate the component/state-time alignment, and component-state occupation probabilities \( \gamma_t(j, m) \): the probability of occupying mixture component \( m \) of state \( j \) at time \( t \).

\((\xi_{tm}(j)) \text{ in Jurafsky and Martin's SLP}\)

We can thus re-estimate the mean of mixture component \( m \) of state \( j \) as follows

\[
\hat{\mu}_{jm} = \frac{\sum_{t=1}^{T} \gamma_t(j, m) x_t}{\sum_{t=1}^{T} \gamma_t(j, m)}
\]

And likewise for the covariance matrices (mixture models often use diagonal covariance matrices)

The mixture coefficients are re-estimated in a similar way to transition probabilities:

\[
\hat{c}_{jm} = \frac{\sum_{t=1}^{T} \gamma_t(j, m)}{\sum_{m'=1}^{M} \sum_{t=1}^{T} \gamma_t(j, m')}
\]
The forward, backward and Viterbi recursions result in a long sequence of probabilities being multiplied. This can cause floating point underflow problems. In practice computations are performed in the log domain (in which multiplies become adds). Working in the log domain also avoids needing to perform the exponentiation when computing Gaussians.
A note on HMM topology

left-to-right model

parallel path left-to-right model

ergodic model

$$\begin{pmatrix}
a_{11} & a_{12} & 0 \\
0 & a_{22} & a_{23} \\
0 & 0 & a_{33}
\end{pmatrix}$$

$$\begin{pmatrix}
a_{11} & a_{12} & a_{13} & 0 & 0 \\
0 & a_{22} & a_{23} & a_{24} & 0 \\
0 & 0 & a_{33} & a_{34} & a_{35} \\
0 & 0 & 0 & a_{44} & a_{45} \\
0 & 0 & 0 & 0 & a_{55}
\end{pmatrix}$$

$$\begin{pmatrix}
a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\
a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\
a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\
a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\
a_{51} & a_{52} & a_{53} & a_{54} & a_{55}
\end{pmatrix}$$

Speech recognition: left-to-right HMM with 3 ~ 5 states
Speaker recognition: ergodic HMM
A note on HMM emission probabilities

Emission prob.

<table>
<thead>
<tr>
<th>Continuous (density) HMM</th>
<th>discrete probability</th>
<th>GMM, NN/DNN VQ</th>
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<tbody>
<tr>
<td>Discrete (probability) HMM</td>
<td>continuous density</td>
<td>tied mixture</td>
</tr>
<tr>
<td>Semi-continuous HMM (tied-mixture HMM)</td>
<td>continuous density</td>
<td></td>
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</tbody>
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Summary: HMMs

- HMMs provide a generative model for statistical speech recognition
- Three key problems
  1. Computing the overall likelihood: the Forward algorithm
  2. Decoding the most likely state sequence: the Viterbi algorithm
  3. Estimating the most likely parameters: the EM (Forward-Backward) algorithm
- Solutions to these problems are tractable due to the two key HMM assumptions
  1. Conditional independence of observations given the current state
  2. Markov assumption on the states

