

Hidden Markov Models and Gaussian Mixture Models

Hiroshi Shimodaira and Steve Renals

Automatic Speech Recognition— ASR Lectures 4&5
26&30 January 2017

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)

Fundamental Equation of Statistical Speech Recognition

If \mathbf{X} is the sequence of acoustic feature vectors (observations) and \mathbf{W} denotes a word sequence, the most likely word sequence \mathbf{W}^* is given by

$$\mathbf{W}^* = \arg \max_{\mathbf{W}} P(\mathbf{W} | \mathbf{X})$$

Applying Bayes' Theorem:

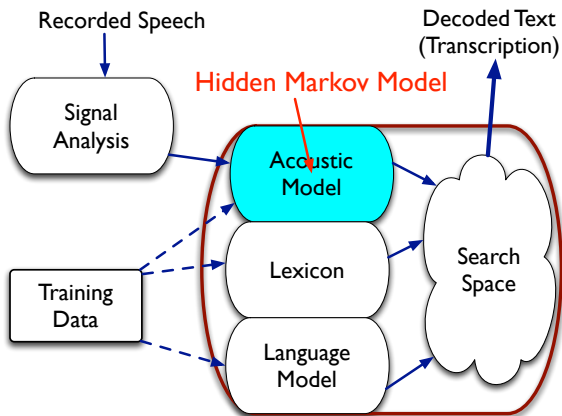
$$P(\mathbf{W} | \mathbf{X}) = \frac{p(\mathbf{X} | \mathbf{W}) P(\mathbf{W})}{p(\mathbf{X})}$$

$$\propto p(\mathbf{X} | \mathbf{W}) P(\mathbf{W})$$

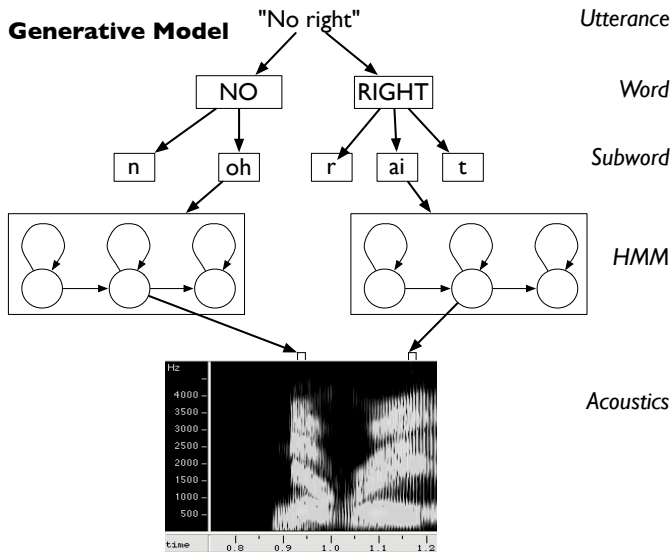
$$\mathbf{W}^* = \arg \max_{\mathbf{W}} \underbrace{p(\mathbf{X} | \mathbf{W})}_{\substack{\text{Acoustic} \\ \text{model}}} \underbrace{P(\mathbf{W})}_{\substack{\text{Language} \\ \text{model}}}$$

NB: \mathbf{X} is used hereafter to denote the output feature vectors from the signal analysis module rather than DFT spectrum.

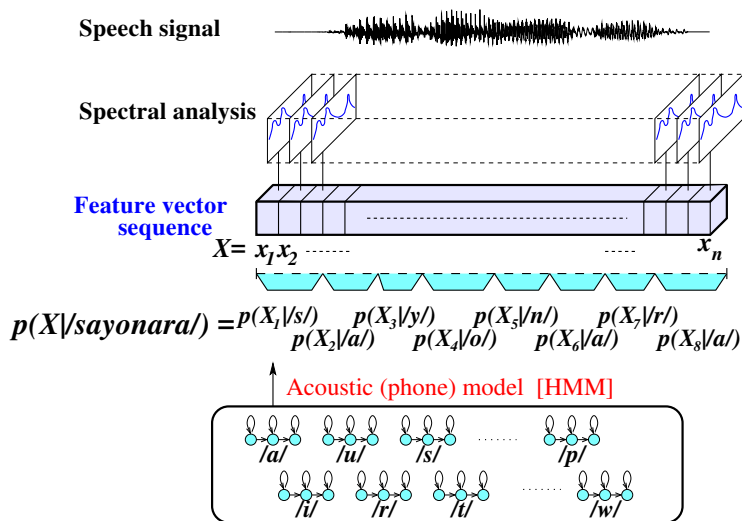
Acoustic Modelling



Hierarchical modelling of speech



Calculation of $p(X|W)$



NB: some conditional independency is assumed here.

How to calculate $p(X_1|/s/)$?

Assume $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_{T_1}$ corresponds to phoneme $/s/$,
the *conditional probability* that we observe the sequence is

$$p(X_1|/s/) = p(\mathbf{x}_1, \dots, \mathbf{x}_{T_1}|/s/), \quad \mathbf{x}_i = (x_{1i}, \dots, x_{di})^t \in \mathcal{R}^d$$

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 \mathbf{x} is one ($d = 1$), so that we don't need HMM.

$$p(X_1|/s/) \longrightarrow p(x_1|/s/)$$

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:

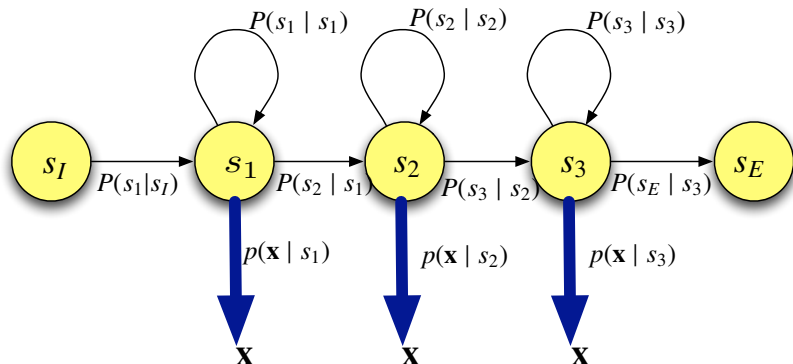
$$P(x|/s/) = \frac{1}{\sqrt{2\pi\sigma_s^2}} e^{-\frac{(x-\mu_s)^2}{2\sigma_s^2}}$$

- The function has only two parameters, μ_s and σ_s^2
- Given a set of training samples $\{x_1, \dots, x_N\}$, we can estimate μ_s and σ_s

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

- For a general case where a phone lasts more than one frame, we need to employ HMM.

Acoustic Model: Continuous Density HMM



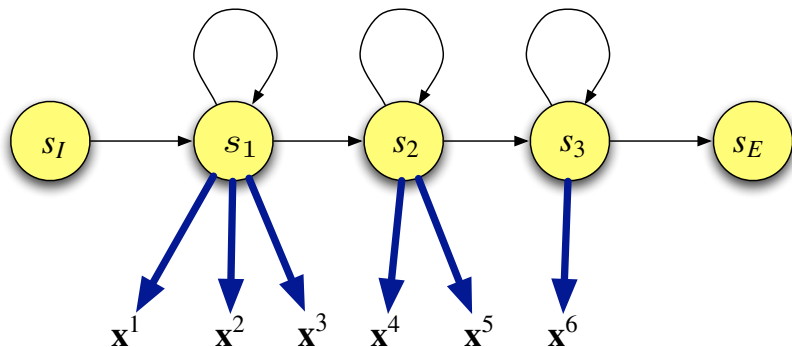
Probabilistic finite state automaton

Parameters λ :

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

NB: Some textbooks use Q or q to denote the state variable S .
 \mathbf{x} corresponds to \mathbf{o}_t in Lecture slides 02.

Acoustic Model: Continuous Density HMM



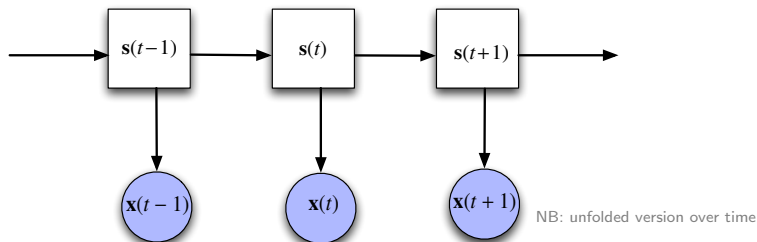
Probabilistic finite state automaton

Parameters λ :

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

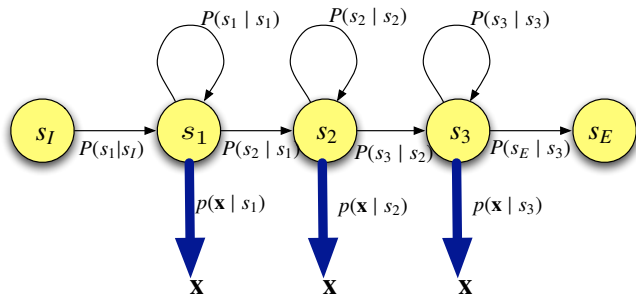
NB: Some textbooks use Q or q to denote the state variable S .
 \mathbf{x} corresponds to \mathbf{o}_t in Lecture slides 02.

HMM Assumptions



- 1 Markov process:** The probability of a state depends only on the previous state: $P(S(t) | S(t-1), S(t-2), \dots, S(1)) = P(S(t) | S(t-1))$
A state is conditionally independent of all other states given the previous state
- 2 Observation independence:** The output observation $\mathbf{x}(t)$ depends only on the state that produced the observation:
 $p(\mathbf{x}(t) | S(t), S(t-1), \dots, S(1), \mathbf{x}(t-1), \dots, \mathbf{x}(1)) = p(\mathbf{x}(t) | S(t))$
An acoustic observation \mathbf{x} is conditionally independent of all other observations given the state that generated it

Output distribution



- Single multivariate Gaussian with mean μ_j , covariance matrix Σ_j :

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

- M -component Gaussian mixture model:

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

- Neural network:

$$b_j(\mathbf{x}) \sim P(S=j | \mathbf{x}) / P(S=j) \quad \text{NB: NN outputs posterior probabilities}$$

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:

$$\begin{aligned} P(a < X \leq b) &= P(X \leq b) - P(X \leq a) \\ &= F(b) - F(a) \end{aligned}$$

- 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)

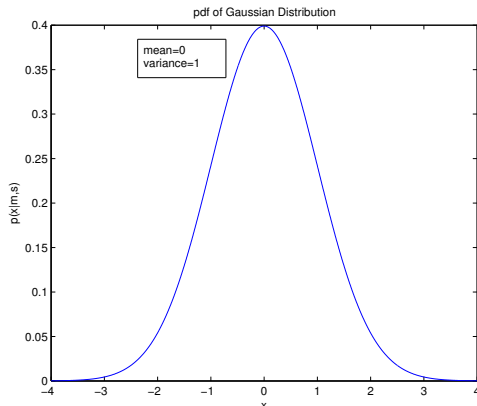
- The **Gaussian** (or **Normal**) distribution is the most common (and easily analysed) continuous distribution
- It is also a reasonable model in many situations (the famous “bell curve”)
- If a (scalar) variable has a Gaussian distribution, then it has a probability density function with this form:

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

- The Gaussian is described by two parameters:
 - the mean μ (location)
 - the variance σ^2 (dispersion)

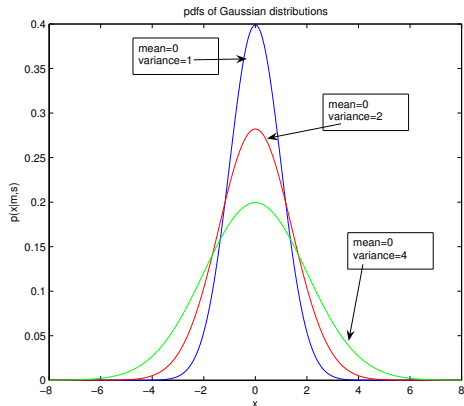
Plot of Gaussian distribution

- 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

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



- Estimate mean and variance parameters of a Gaussian from data x_1, x_2, \dots, 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 $\{x_1, \dots, x_T\}$ being generated by a Gaussian with mean μ and variance σ^2 :

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

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

$$\mu_{ML} = \frac{1}{T} \sum_{t=1}^T x_t.$$

The multivariate Gaussian distribution

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

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

The pdf is parameterized by the mean vector $\boldsymbol{\mu} = (\mu_1, \dots, \mu_D)^T$

and the covariance matrix $\boldsymbol{\Sigma} = \begin{pmatrix} \sigma_{11} & \dots & \sigma_{1D} \\ \vdots & \ddots & \vdots \\ \sigma_{D1} & \dots & \sigma_{DD} \end{pmatrix}$.

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

Covariance matrix

- The mean vector $\boldsymbol{\mu}$ is the expectation of \mathbf{x} :

$$\boldsymbol{\mu} = E[\mathbf{x}]$$

- The covariance matrix $\boldsymbol{\Sigma}$ is the expectation of the deviation of \mathbf{x} from the mean:

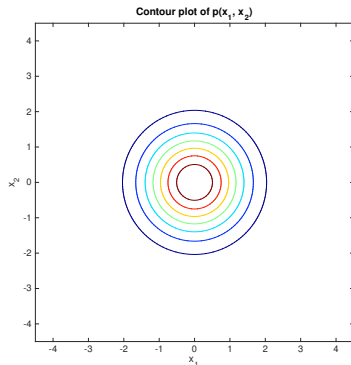
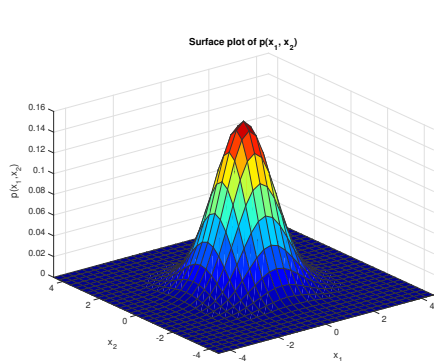
$$\boldsymbol{\Sigma} = E[(\mathbf{x} - \boldsymbol{\mu})(\mathbf{x} - \boldsymbol{\mu})^T]$$

- $\boldsymbol{\Sigma}$ 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.

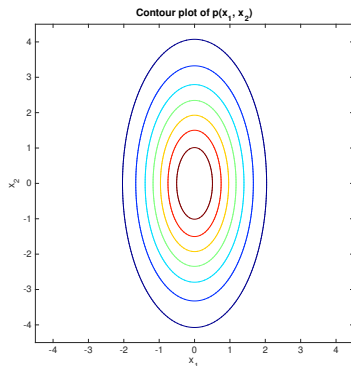
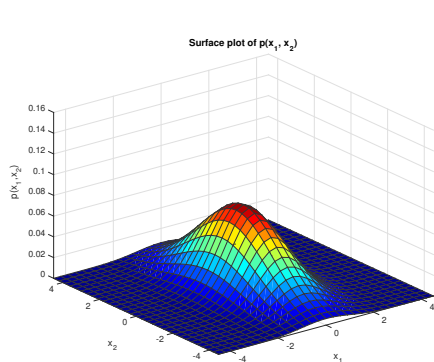
Spherical Gaussian



$$\boldsymbol{\mu} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \boldsymbol{\Sigma} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \rho_{12} = 0$$

NB: Correlation coefficient $\rho_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii}\sigma_{jj}}}$ ($-1 \leq \rho_{ij} \leq 1$)

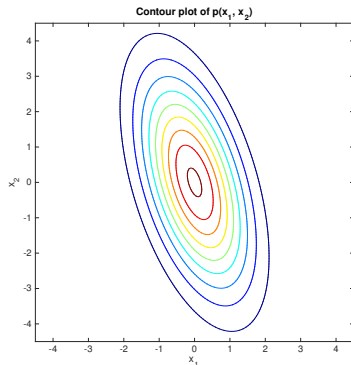
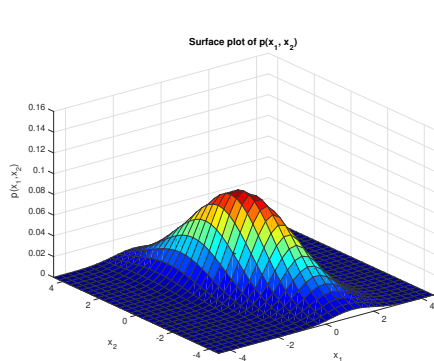
Diagonal Covariance Gaussian



$$\mu = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \Sigma = \begin{pmatrix} 1 & 0 \\ 0 & 4 \end{pmatrix} \quad \rho_{12} = 0$$

NB: Correlation coefficient $\rho_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii}\sigma_{jj}}}$ ($-1 \leq \rho_{ij} \leq 1$)

Full covariance Gaussian



$$\boldsymbol{\mu} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \boldsymbol{\Sigma} = \begin{pmatrix} 1 & -1 \\ -1 & 4 \end{pmatrix} \quad \rho_{12} = -0.5$$

NB: Correlation coefficient $\rho_{ij} = \frac{\sigma_{ij}}{\sqrt{\sigma_{ii}\sigma_{jj}}}$ ($-1 \leq \rho_{ij} \leq 1$)

Parameter estimation of a multivariate Gaussian distribution

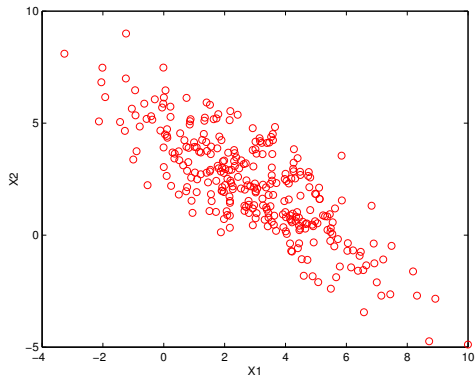
- It is possible to show that the mean vector $\hat{\boldsymbol{\mu}}$ and covariance matrix $\hat{\boldsymbol{\Sigma}}$ that maximize the likelihood of the training data are given by:

$$\hat{\boldsymbol{\mu}} = \frac{1}{T} \sum_{t=1}^T \mathbf{x}_t$$
$$\hat{\boldsymbol{\Sigma}} = \frac{1}{T} \sum_{t=1}^T (\mathbf{x}_t - \hat{\boldsymbol{\mu}})(\mathbf{x}_t - \hat{\boldsymbol{\mu}})^T$$

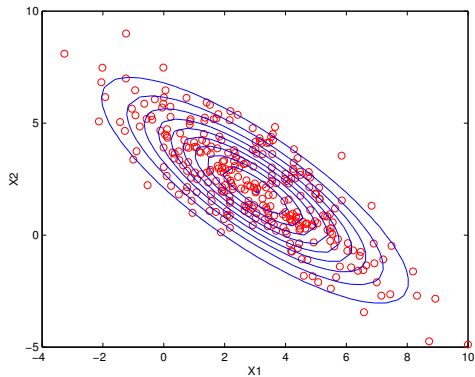
where $\mathbf{x}_t = (x_{t1}, \dots, x_{tD})^T$.

NB: T denotes either the number of samples or vector transpose depending on context.

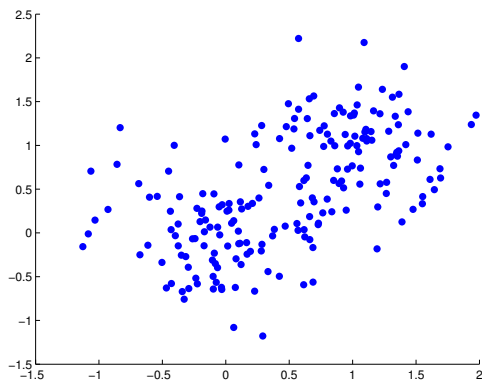
Example data



Maximum likelihood fit to a Gaussian

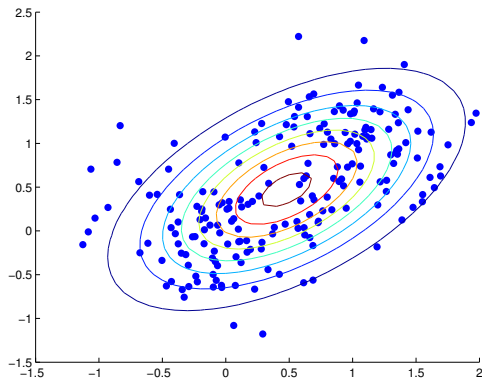


Data in clusters (example 1)



$$\mu_1 = (0, 0)^T \quad \mu_2 = (1, 1)^T \quad \Sigma_1 = \Sigma_2 = 0.2\mathbf{I}$$

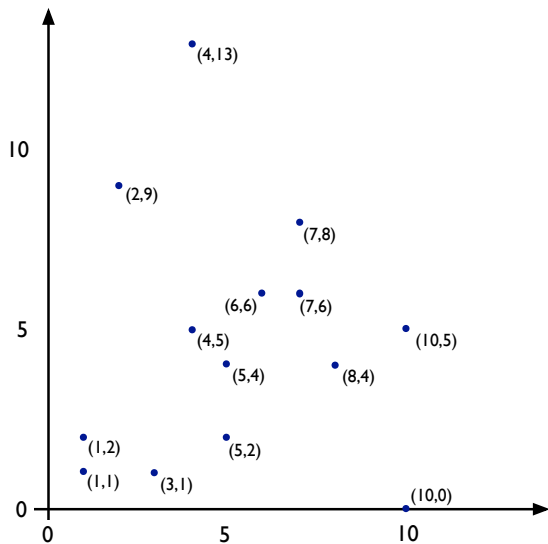
Example 1 fit by a Gaussian



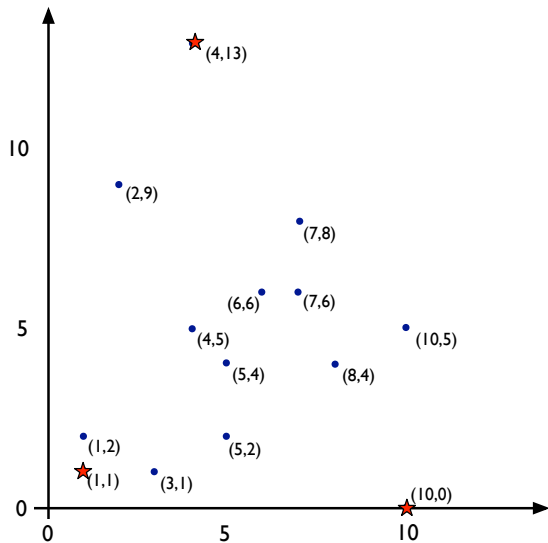
$$\mu_1 = (0, 0)^T \quad \mu_2 = (1, 1)^T \quad \Sigma_1 = \Sigma_2 = 0.2\mathbf{I}$$

- 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

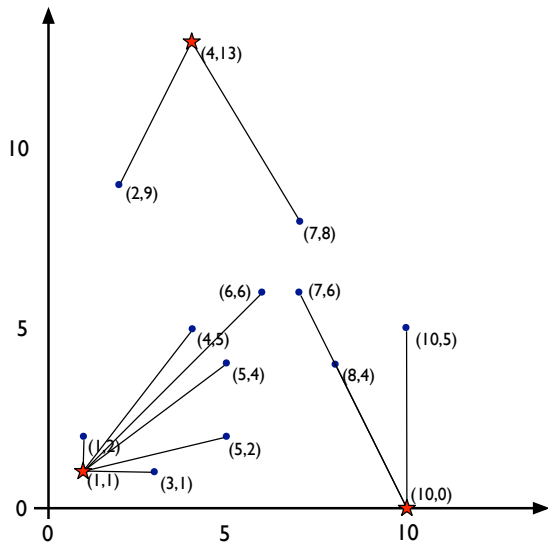
k-means example: data set



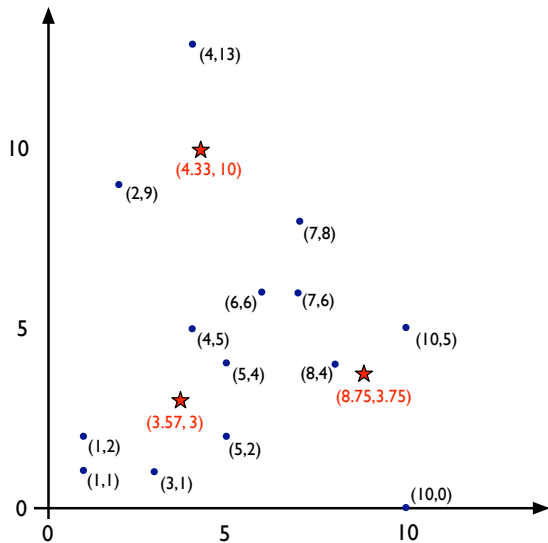
k-means example: initialization



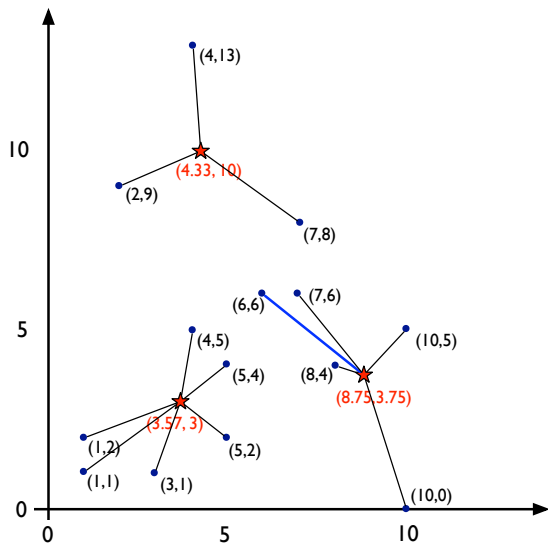
k-means example: iteration 1 (assign points to clusters)



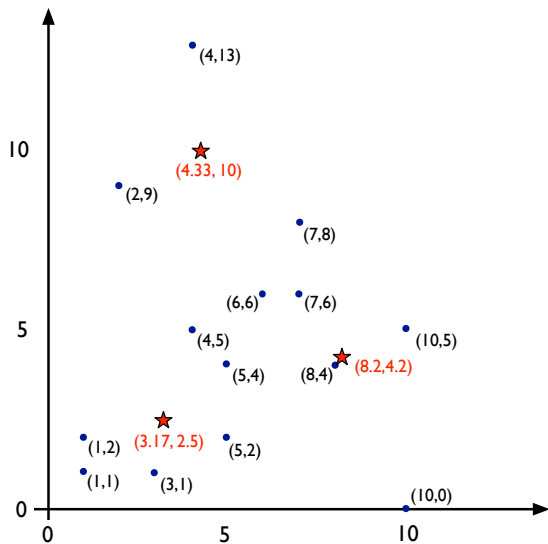
k-means example: iteration 1 (recompute centres)



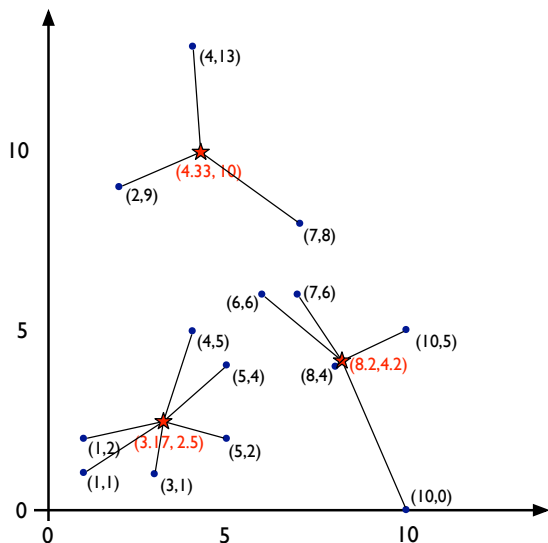
k-means example: iteration 2 (assign points to clusters)



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:

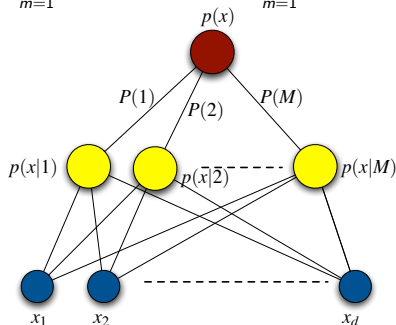
$$p(\mathbf{x}) = \sum_{m=1}^M p(\mathbf{x} | m)P(m)$$

- This is called a *mixture model* or a *mixture density*
- $p(\mathbf{x} | m)$: component densities
- $P(m)$: mixing parameters
- Generative model:
 - 1 Choose a mixture component based on $P(m)$
 - 2 Generate a data point \mathbf{x} from the chosen component using $p(\mathbf{x} | m)$

Gaussian mixture model

- The most important mixture model is the *Gaussian Mixture Model* (GMM), where the component densities are Gaussians
- Consider a GMM, where each component Gaussian $\mathcal{N}(\mathbf{x}; \boldsymbol{\mu}_m, \boldsymbol{\Sigma}_m)$ has mean $\boldsymbol{\mu}_m$ and a **spherical covariance** $\boldsymbol{\Sigma}_m = \sigma_m^2 \mathbf{I}$

$$p(\mathbf{x}) = \sum_{m=1}^M P(m) p(\mathbf{x} | m) = \sum_{m=1}^M P(m) \mathcal{N}(\mathbf{x}; \boldsymbol{\mu}_m, \sigma_m^2 \mathbf{I})$$



GMM Parameter estimation when we know which component generated the data

- Define the indicator variable $z_{mt} = 1$ if component m generated data point \mathbf{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:

$$\hat{\boldsymbol{\mu}}_m = \frac{\sum_t z_{mt} \mathbf{x}_t}{N_m}$$

$$\hat{\sigma}_m^2 = \frac{\sum_t z_{mt} \|\mathbf{x}_t - \hat{\boldsymbol{\mu}}_m\|^2}{N_m}$$

$$\hat{P}(m) = \frac{1}{T} \sum_t z_{mt} = \frac{N_m}{T}$$

GMM Parameter estimation when we don't know which component generated the data

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

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

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

$$\sum_{m=1}^M P(m|\mathbf{x}) = 1$$

Soft assignment

- Estimate “soft counts” based on the component occupation probabilities $P(m|\mathbf{x}_t)$:

$$N_m^* = \sum_{t=1}^T P(m|\mathbf{x}_t)$$

- We can imagine assigning data points to component m weighted by the component occupation probability $P(m|\mathbf{x}_t)$
- So we could imagine estimating the mean, variance and prior probabilities as:

$$\hat{\boldsymbol{\mu}}_m = \frac{\sum_t P(m|\mathbf{x}_t)\mathbf{x}_t}{\sum_t P(m|\mathbf{x}_t)} = \frac{\sum_t P(m|\mathbf{x}_t)\mathbf{x}_t}{N_m^*}$$

$$\hat{\sigma}_m^2 = \frac{\sum_t P(m|\mathbf{x}_t) \|\mathbf{x}_t - \hat{\boldsymbol{\mu}}_m\|^2}{\sum_t P(m|\mathbf{x}_t)} = \frac{\sum_t P(m|\mathbf{x}_t) \|\mathbf{x}_t - \hat{\boldsymbol{\mu}}_m\|^2}{N_m^*}$$

$$\hat{P}(m) = \frac{1}{T} \sum_t P(m|\mathbf{x}_t) = \frac{N_m^*}{T}$$

- *Problem!* Recall that:

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

We need to know $p(\mathbf{x}|m)$ and $P(m)$ to estimate the parameters of $P(m|\mathbf{x})$, and to estimate $P(m)$

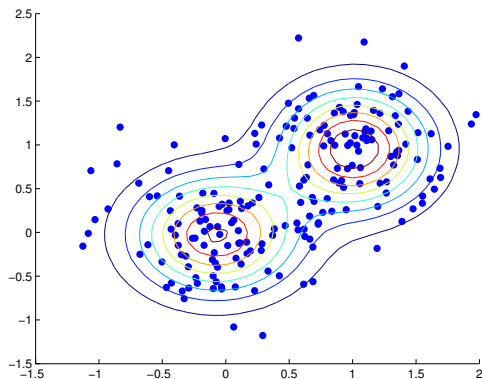
- Solution: an iterative algorithm where each iteration has two parts:
 - Compute the component occupation probabilities $P(m|\mathbf{x})$ using the current estimates of the GMM parameters (means, variances, mixing parameters) (E-step)
 - Compute the GMM parameters using the current estimates of the component occupation probabilities (M-step)
- Starting from some initialization (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 maximize the likelihood

- The likelihood of a data set $\mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_T\}$ is given by:

$$\mathcal{L} = \prod_{t=1}^T p(\mathbf{x}_t) = \prod_{t=1}^T \sum_{m=1}^M p(\mathbf{x}_t | m) P(m)$$

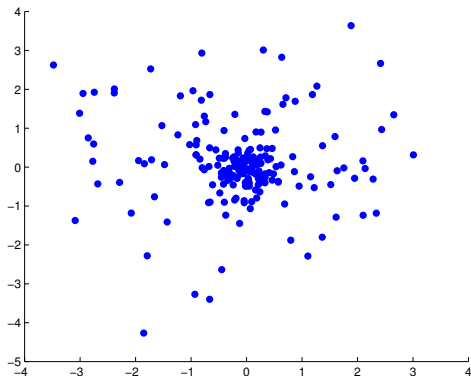
- We can regard the *negative log likelihood* as an error function:
- Considering the derivatives of E with respect to the parameters, gives expressions like the previous slide

Example 1 fit using a GMM



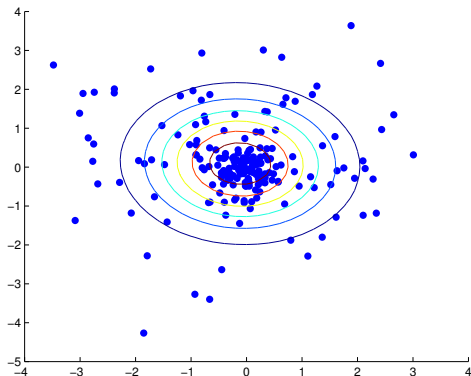
Fitted with a two component GMM using EM

Peakily distributed data (Example 2)



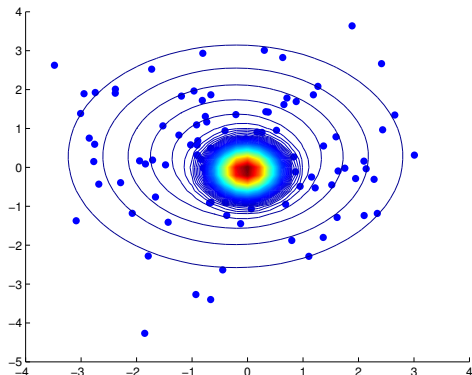
$$\mu_1 = \mu_2 = [0 \quad 0]^T \quad \Sigma_1 = 0.1\mathbf{I} \quad \Sigma_2 = 2\mathbf{I}$$

Example 2 fit by a Gaussian



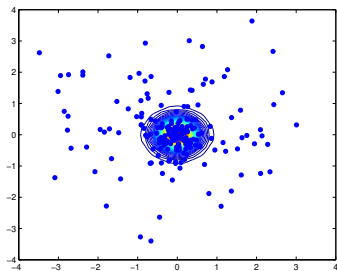
$$\mu_1 = \mu_2 = [0 \quad 0]^T \quad \Sigma_1 = 0.1\mathbf{I} \quad \Sigma_2 = 2\mathbf{I}$$

Example 2 fit by a GMM

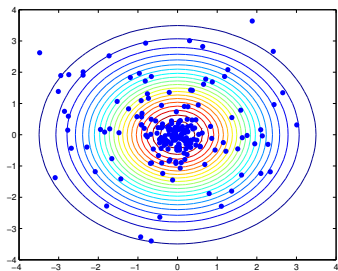


Fitted with a two component GMM using EM

Example 2: component Gaussians



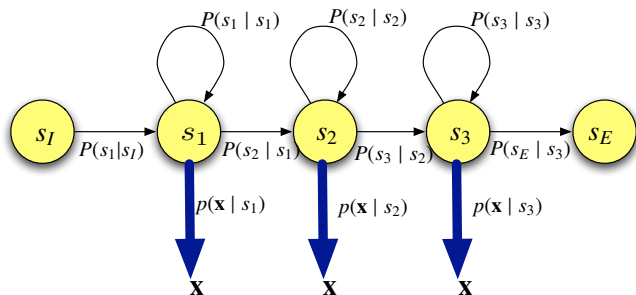
$$P(\mathbf{x} | m=1)$$



$$P(\mathbf{x} | m=2)$$

- GMMs trained using the EM algorithm are able to self organize 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

Back to HMMs...



Output distribution:

- Single multivariate Gaussian with mean μ_j , covariance matrix Σ_j :

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

- M -component Gaussian mixture model:

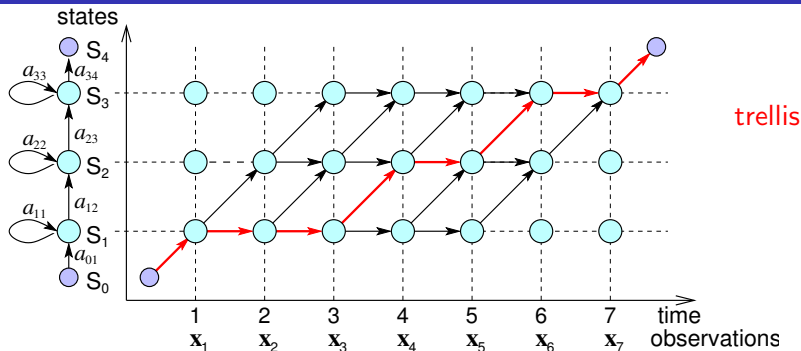
$$b_j(\mathbf{x}) = p(\mathbf{x} | S=j) = \sum_{m=1}^M c_{jm} \mathcal{N}(\mathbf{x}; \mu_{jm}, \Sigma_{jm})$$

The three problems of HMMs

Working with HMMs requires the solution of three problems:

- 1 **Likelihood** Determine the overall likelihood of an observation sequence $\mathbf{X} = (\mathbf{x}_1, \dots, \mathbf{x}_t, \dots, \mathbf{x}_T)$ 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 $\lambda = \{\{a_{jk}\}, \{b_j(\cdot)\}\}$

1. Likelihood: how to calculate?

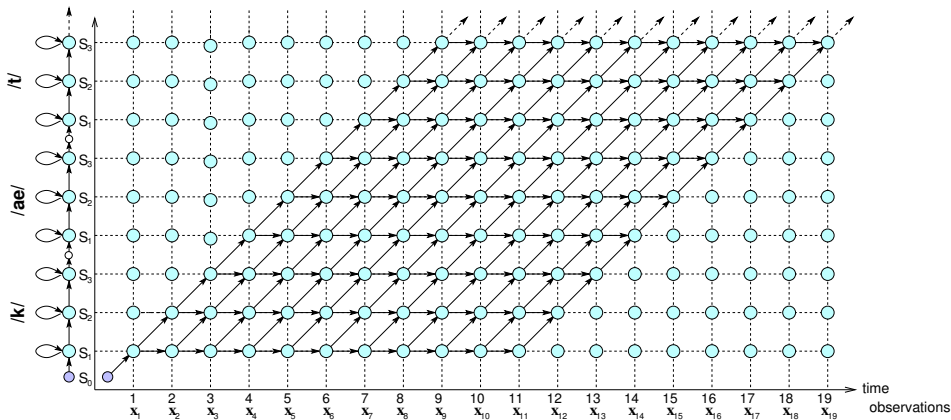


$$\begin{aligned}
 P(\mathbf{X}, \text{path}_\ell | \lambda) &= P(\mathbf{X} | \text{path}_\ell, \lambda) P(\text{path}_\ell | \lambda) \\
 &= P(\mathbf{X} | s_0 s_1 s_1 s_1 s_2 s_2 s_3 s_3 s_4, \lambda) P(s_0 s_1 s_1 s_1 s_2 s_2 s_3 s_3 s_4 | \lambda) \\
 &= b_1(\mathbf{x}_1) b_1(\mathbf{x}_2) b_1(\mathbf{x}_3) b_2(\mathbf{x}_4) b_2(\mathbf{x}_5) b_3(\mathbf{x}_6) b_3(\mathbf{x}_7) a_{01} a_{11} a_{11} a_{12} a_{22} a_{23} a_{33} a_{34}
 \end{aligned}$$

$$P(\mathbf{X} | \lambda) = \sum_{\{\text{path}_\ell\}} P(\mathbf{X}, \text{path}_\ell | \lambda) \simeq \max_{\text{path}_\ell} P(\mathbf{X}, \text{path}_\ell | \lambda)$$

forward(backward) algorithm Viterbi algorithm

Trellis for /k ae t/



1. Likelihood: The Forward algorithm

- Goal: determine $p(\mathbf{X}|\lambda)$
- Sum over all possible state sequences $s_1 s_2 \dots s_T$ 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 $p(\mathbf{X}|\lambda)$?

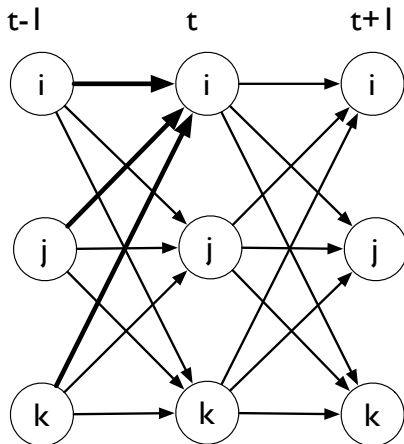
$$\sim \underbrace{N \times N \times \dots \times N}_{T \text{ times}} = N^T \quad \begin{array}{l} N : \text{ number of HMM states} \\ T : \text{ length of observation} \end{array}$$

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

- Computation complexity of multiplication: $O(2T N^T)$
- The Forward algorithm reduces this to $O(TN^2)$

Recursive algorithms on HMMs

Visualize the problem as a *state-time trellis*



1. Likelihood: The Forward algorithm

- Goal: determine $p(\mathbf{X} | \lambda)$
- Sum over all possible state sequences $s_1 s_2 \dots s_T$ that could result in the observation sequence \mathbf{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 $\mathbf{x}_1 \dots \mathbf{x}_t$ and being in state j at time t :

$$\alpha_t(j) = p(\mathbf{x}_1, \dots, \mathbf{x}_t, S(t)=j | \lambda)$$

1. Likelihood: The Forward recursion

- Initialization

$$\begin{aligned}\alpha_0(s_I) &= 1 \\ \alpha_0(j) &= 0 \quad \text{if } j \neq s_I\end{aligned}$$

- Recursion

$$\alpha_t(j) = \sum_{i=1}^N \alpha_{t-1}(i) a_{ij} b_j(\mathbf{x}_t) \quad 1 \leq j \leq N, 1 \leq t \leq T$$

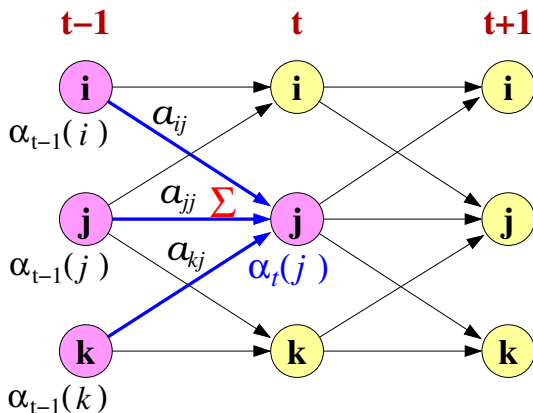
- Termination

$$p(\mathbf{X} | \boldsymbol{\lambda}) = \alpha_T(s_E) = \sum_{i=1}^N \alpha_T(i) a_{iE}$$

s_I : initial state, s_E : final state

1. Likelihood: Forward Recursion

$$\alpha_t(j) = p(\mathbf{x}_1, \dots, \mathbf{x}_t, S(t)=j | \lambda) = \sum_{i=1}^N \alpha_{t-1}(i) a_{ij} b_j(\mathbf{x}_t)$$



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:

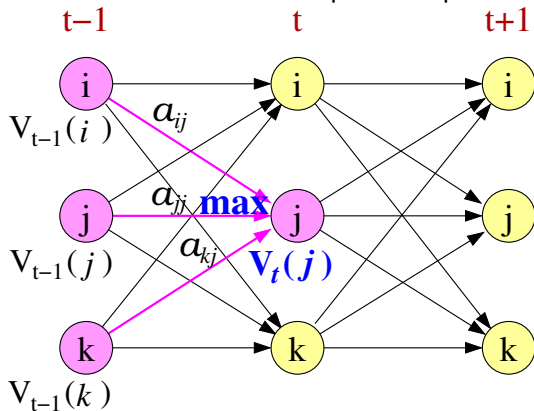
$$V_t(j) = \max_i V_{t-1}(i) a_{ij} b_j(\mathbf{x}_t)$$

- 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 *backpointers* to enable a Viterbi *backtrace*: the backpointer for each state at each time indicates the previous state on the most probable path

Viterbi Recursion

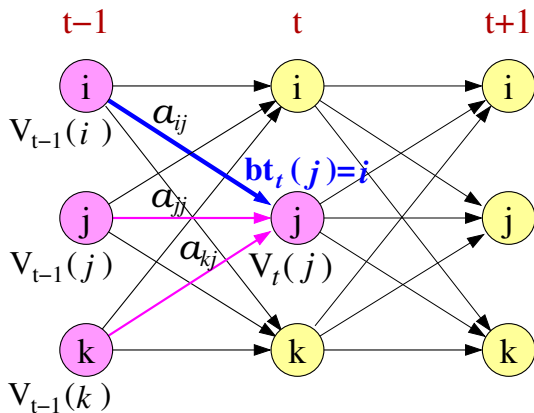
$$V_t(j) = \max_i V_{t-1}(i) a_{ij} b_j(\mathbf{x}_t)$$

Likelihood of the most probable path



Viterbi Recursion

Backpointers to the previous state on the most probable path



2. Decoding: The Viterbi algorithm

- Initialization

$$V_0(i) = 1$$

$$V_0(j) = 0 \quad \text{if } j \neq i$$

$$bt_0(j) = 0$$

- Recursion

$$V_t(j) = \max_{i=1}^N V_{t-1}(i) a_{ij} b_j(\mathbf{x}_t)$$

$$bt_t(j) = \arg \max_{i=1}^N V_{t-1}(i) a_{ij} b_j(\mathbf{x}_t)$$

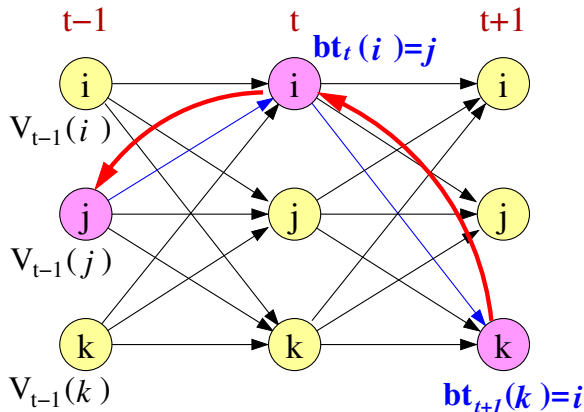
- Termination

$$P^* = V_T(s_E) = \max_{i=1}^N V_T(i) a_{iE}$$

$$s_T^* = bt_T(q_E) = \arg \max_{i=1}^N V_T(i) a_{iE}$$

Viterbi Backtrace

Backtrace to find the state sequence of the most probable path



3. Training: Forward-Backward algorithm

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

$$b_j(\mathbf{x}) = p(\mathbf{x} | j) = \mathcal{N}(\mathbf{x}; \boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j)$$

- Parameters λ :
 - Transition probabilities a_{ij} :

$$\sum_j a_{ij} = 1$$

- Gaussian parameters for state j :
mean vector $\boldsymbol{\mu}_j$; covariance matrix $\boldsymbol{\Sigma}_j$

- 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:

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

- 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)

Backward probabilities

- To estimate the state occupation probabilities it is useful to define (recursively) another set of probabilities—the *Backward* probabilities

$$\beta_t(j) = p(\mathbf{x}_{t+1}, \dots, \mathbf{x}_T | S(t)=j, \lambda)$$

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

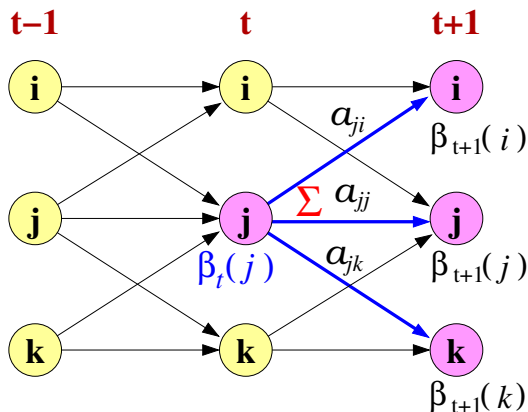
$$\beta_t(i) = \sum_{j=1}^N a_{ij} b_j(\mathbf{x}_{t+1}) \beta_{t+1}(j) \quad \text{for } t = T-1, \dots, 1$$

- Termination

$$p(\mathbf{X} | \lambda) = \beta_0(I) = \sum_{j=1}^N a_{Ij} b_j(\mathbf{x}_1) \beta_1(j) = \alpha_T(s_E)$$

Backward Recursion

$$\beta_t(j) = p(\mathbf{x}_{t+1}, \dots, \mathbf{x}_T | S(t)=j, \lambda) = \sum_{j=1}^N a_{ij} b_j(\mathbf{x}_{t+1}) \beta_{t+1}(j)$$



State Occupation Probability

- 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:

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

recalling that $p(\mathbf{X} | \lambda) = \alpha_T(s_E)$

- Since

$$\begin{aligned} \alpha_t(j) \beta_t(j) &= p(\mathbf{x}_1, \dots, \mathbf{x}_t, S(t)=j | \lambda) \\ &\quad p(\mathbf{x}_{t+1}, \dots, \mathbf{x}_T | S(t)=j, \lambda) \\ &= p(\mathbf{x}_1, \dots, \mathbf{x}_t, \mathbf{x}_{t+1}, \dots, \mathbf{x}_T, S(t)=j | \lambda) \\ &= p(\mathbf{X}, S(t)=j | \lambda) \end{aligned}$$

$$P(S(t)=j | \mathbf{X}, \lambda) = \frac{p(\mathbf{X}, S(t)=j | \lambda)}{p(\mathbf{X} | \lambda)}$$

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:

$$\hat{\boldsymbol{\mu}}_j = \frac{\sum_{t=1}^T \gamma_t(j) \mathbf{x}_t}{\sum_{t=1}^T \gamma_t(j)}$$
$$\hat{\boldsymbol{\Sigma}}_j = \frac{\sum_{t=1}^T \gamma_t(j) (\mathbf{x}_t - \hat{\boldsymbol{\mu}}_j)(\mathbf{x}_t - \hat{\boldsymbol{\mu}}_j)^T}{\sum_{t=1}^T \gamma_t(j)}$$

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:

$$\begin{aligned}\xi_t(i, j) &= P(S(t)=i, S(t+1)=j | \mathbf{X}, \lambda) \\ &= \frac{p(S(t)=i, S(t+1)=j, \mathbf{X} | \lambda)}{p(\mathbf{X} | \lambda)} \\ &= \frac{\alpha_t(i) a_{ij} b_j(\mathbf{x}_{t+1}) \beta_{t+1}(j)}{\alpha_T(s_E)}\end{aligned}$$

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

$$\hat{a}_{ij} = \frac{\sum_{t=1}^T \xi_t(i, j)}{\sum_{k=1}^N \sum_{t=1}^T \xi_t(i, k)}$$

Pulling it all together

- 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 μ_j , covariance matrices Σ_j and transition probabilities a_{ij}

- The application of the EM algorithm to HMM training is sometimes called the Forward-Backward algorithm

Extension to a corpus of utterances

- We usually train from a large corpus of R utterances
- If \mathbf{x}_t^r is the t th frame of the r th utterance \mathbf{X}^r then we can compute the probabilities $\alpha_t^r(j)$, $\beta_t^r(j)$, $\gamma_t^r(j)$ and $\xi_t^r(i, j)$ as before
- The re-estimates are as before, except we must sum over the R utterances, eg:

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

- 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)

Extension to Gaussian mixture model (GMM)

- 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:

$$b_j(\mathbf{x}) = p(\mathbf{x} | S=j) = \sum_{m=1}^M c_{jm} \mathcal{N}(\mathbf{x}; \boldsymbol{\mu}_{jm}, \boldsymbol{\Sigma}_{jm})$$

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

EM training of HMM/GMM

- 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 .

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

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

$$\hat{\mu}_{jm} = \frac{\sum_{t=1}^T \gamma_t(j, m) \mathbf{x}_t}{\sum_{t=1}^T \gamma_t(j, m)}$$

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

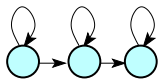
- The mixture coefficients are re-estimated in a similar way to transition probabilities:

$$\hat{c}_{jm} = \frac{\sum_{t=1}^T \gamma_t(j, m)}{\sum_{m'=1}^M \sum_{t=1}^T \gamma_t(j, m')}$$

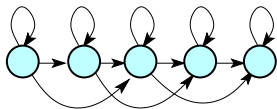
Doing the computation

- 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

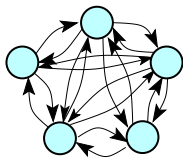
A note on HMM topology



left-to-right model



parallel path left-to-right model



ergodic model

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

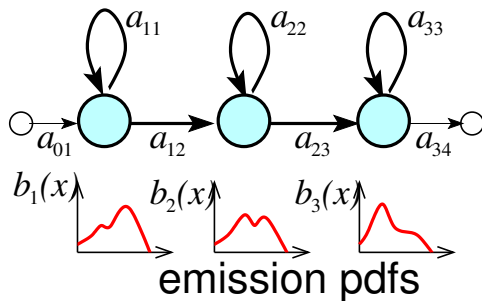
$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 \\ 0 & a_{22} & a_{23} & a_{24} & 0 \\ 0 & 0 & a_{33} & a_{34} & a_{35} \\ 0 & 0 & 0 & a_{44} & a_{45} \\ 0 & 0 & 0 & 0 & a_{55} \end{pmatrix}$$

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

Speech recognition: left-to-right HMM with 3 ~ 5 states

Speaker recognition: ergodic HMM

A note on HMM emission probabilities



	Emission prob.	
Continuous (density) HMM	continuous density	GMM, NN/DNN
Discrete (probability) HMM	discrete probability	VQ
Semi-continuous HMM (tied-mixture HMM)	continuous density	tied mixture

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

- Gales and Young (2007). “The Application of Hidden Markov Models in Speech Recognition”, *Foundations and Trends in Signal Processing*, **1** (3), 195–304: section 2.2.
- Jurafsky and Martin (2008). *Speech and Language Processing* (2nd ed.): sections 6.1–6.5; 9.2; 9.4. (Errata at <http://www.cs.colorado.edu/~martin/SLP/Errata/SLP2-PIEV-Errata.html>)
- Rabiner and Juang (1989). “An introduction to hidden Markov models”, *IEEE ASSP Magazine*, **3** (1), 4–16.
- Renals and Hain (2010). “Speech Recognition”, *Computational Linguistics and Natural Language Processing Handbook*, Clark, Fox and Lappin (eds.), Blackwells.