Automatic Speech Recognition

Machine Learning

Dongsuk Yook
Artificial Intelligence Laboratory
Korea University

Contents

Class Objectives

- Understanding automatic speech recognition
- Being able to apply HMMs to automatic speech recognition

Contents

Applications of HMMs

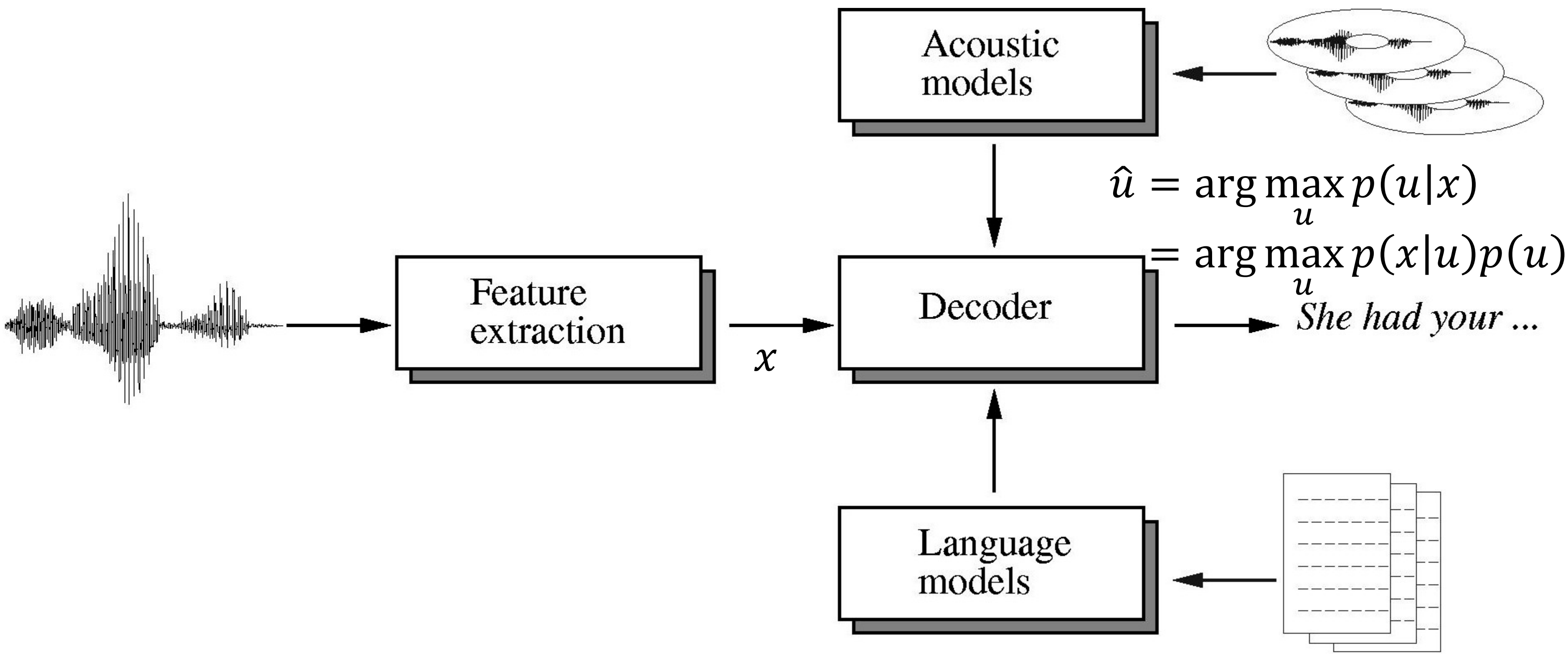
- Automatic speech recognition
- Activity recognition
  - e.g., walking, running, ...
- Part of speech tagging
  - e.g., noun, verb, ...
- Gene finding
- Protein sequence alignment

Automatic Speech Recognition

- Find the most probable utterance $\hat{u}$ for a given input speech x (vector sequence).
  - $$\begin{aligned}\hat{u} &= \arg\max_u p(u|x) \\ &= \arg\max_u \frac{p(x|u)p(u)}{p(x)} \\ &= \arg\max_u p(x|u)p(u)\end{aligned}$$
  - $p(x|u)$: acoustic model probability
  - $p(u)$: language model probability

Overview of Automatic Speech Recognition

$p(x|u)$: acoustic model probability

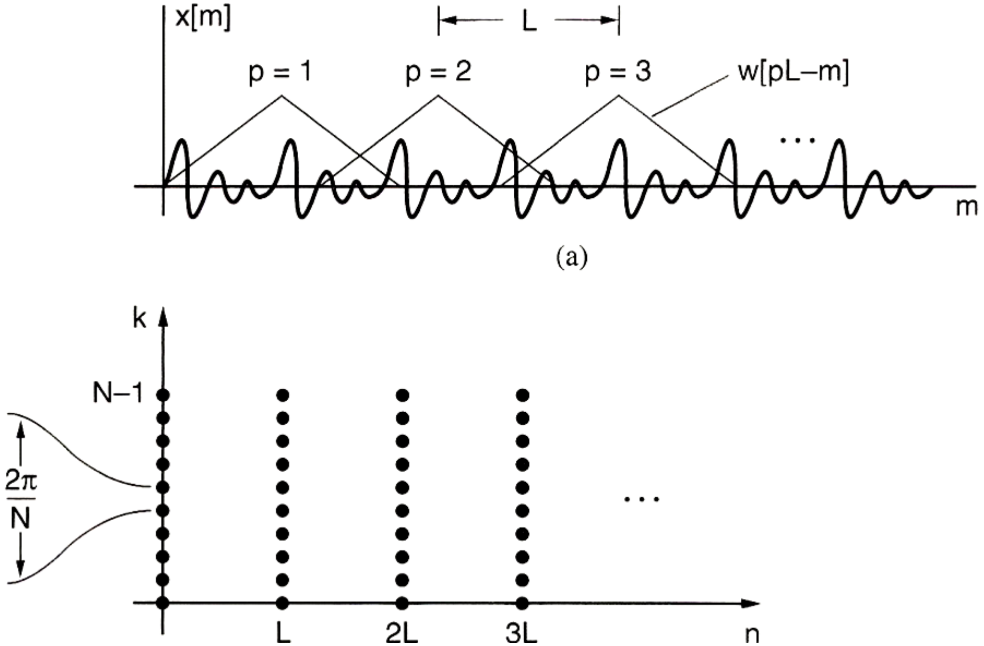


$p(u)$: language model probability

Contents

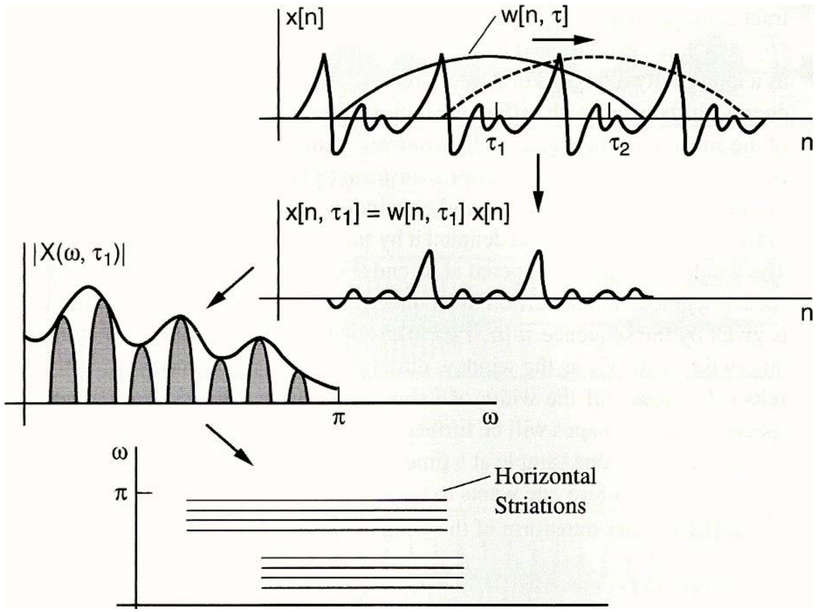
Spectrograms

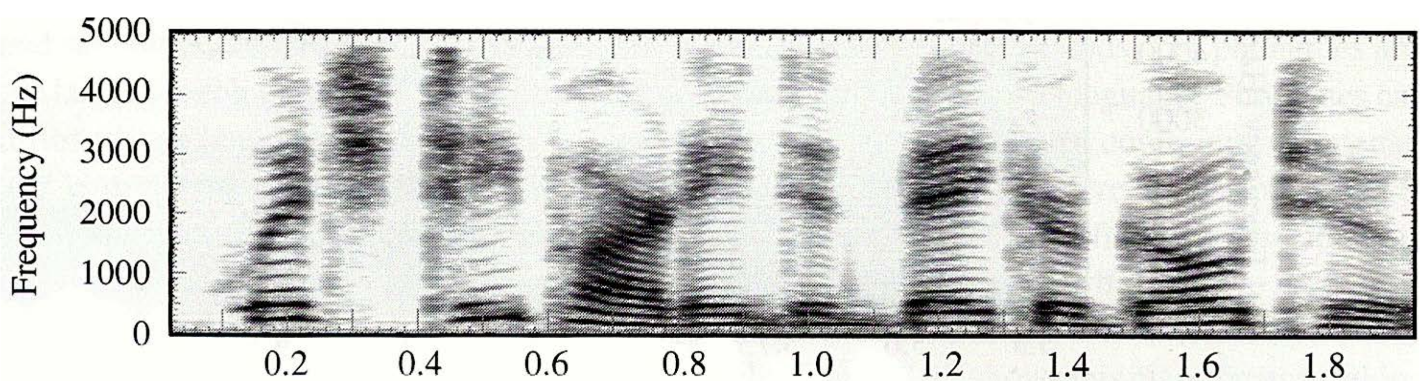
- A single spectrum of the entire acoustic signal for an utterance is not adequate for representing a time-varying characteristic of the signal. Instead, a sequence of spectra is computed using the signal under a sliding window. That is, a sequence of short time Fourier transforms (STFT) is used to represent the time-varying characteristic of a signal. A *spectrogram* is a graphical display of the magnitude of the time-varying spectral characteristic in two-dimensional time-frequency space. The time variation of a signal is typically decimated by a temporal decimation factor. The multiplying windows is typically tapered at its ends to avoid unnatural discontinuities in the windowed segments.



Narrowband Spectrograms

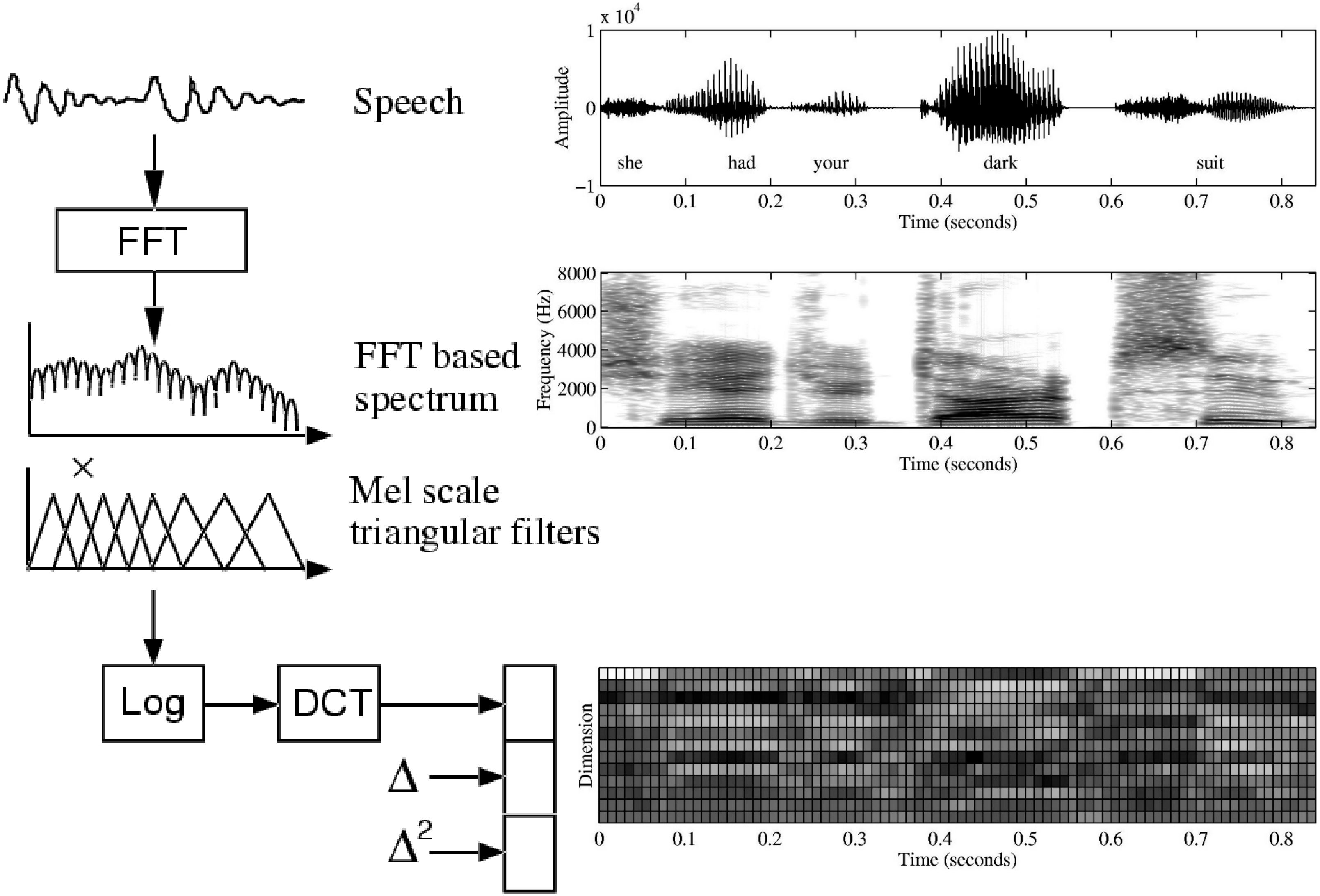
- Narrowband spectrograms
  - The spectra are computed using windowed signals of at least two pitch periods, which give good spectral resolution.





Mel-Frequency Cepstral Coefficients

- Mel-frequency cepstral coefficients (MFCC)



Time Derivatives

- Time derivatives of cepstra
  - First order
    - $$\frac{\partial x_i}{\partial t} = \frac{\sum_{t=1}^{T} t\left(x_i^{t} - x_i^{-t}\right)}{2\sum_{t=1}^{T} t^2}$$
  - Second order
    - $$\frac{\partial^2 x_i}{\partial^2 t} = \frac{\sum_{t=1}^{T} t\left(\frac{\partial x_i^{t}}{\partial t} - \frac{\partial x_i^{t}}{\partial t}\right)}{2\sum_{t=1}^{T} t^2}$$

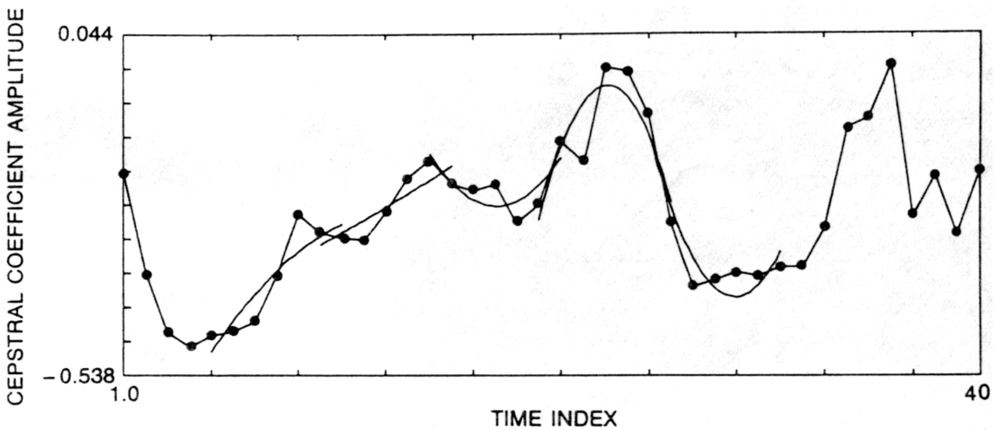
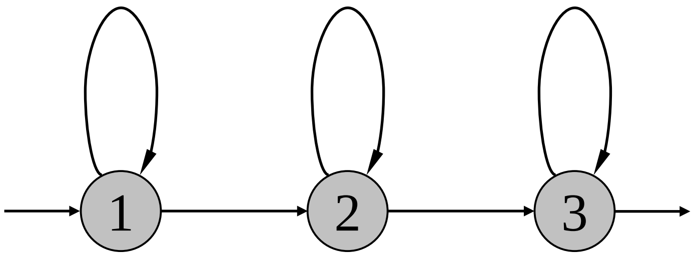
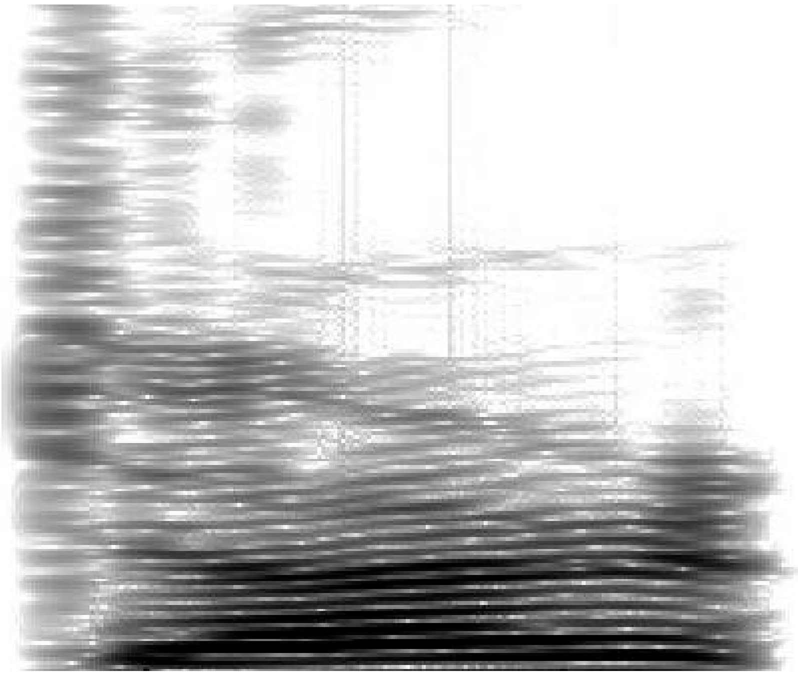


Figure 4.34 A trajectory of the (2nd) cepstral coefficient with 2nd-order polynomial ($h_1 + h_2 t + h_3 t^2$) fitting on short portions of the trajectory; the width for polynomial fitting is 7 points.

Contents

- $p(x|u)$





Context-Dependent Phones

- Words
  - She had your dark suit

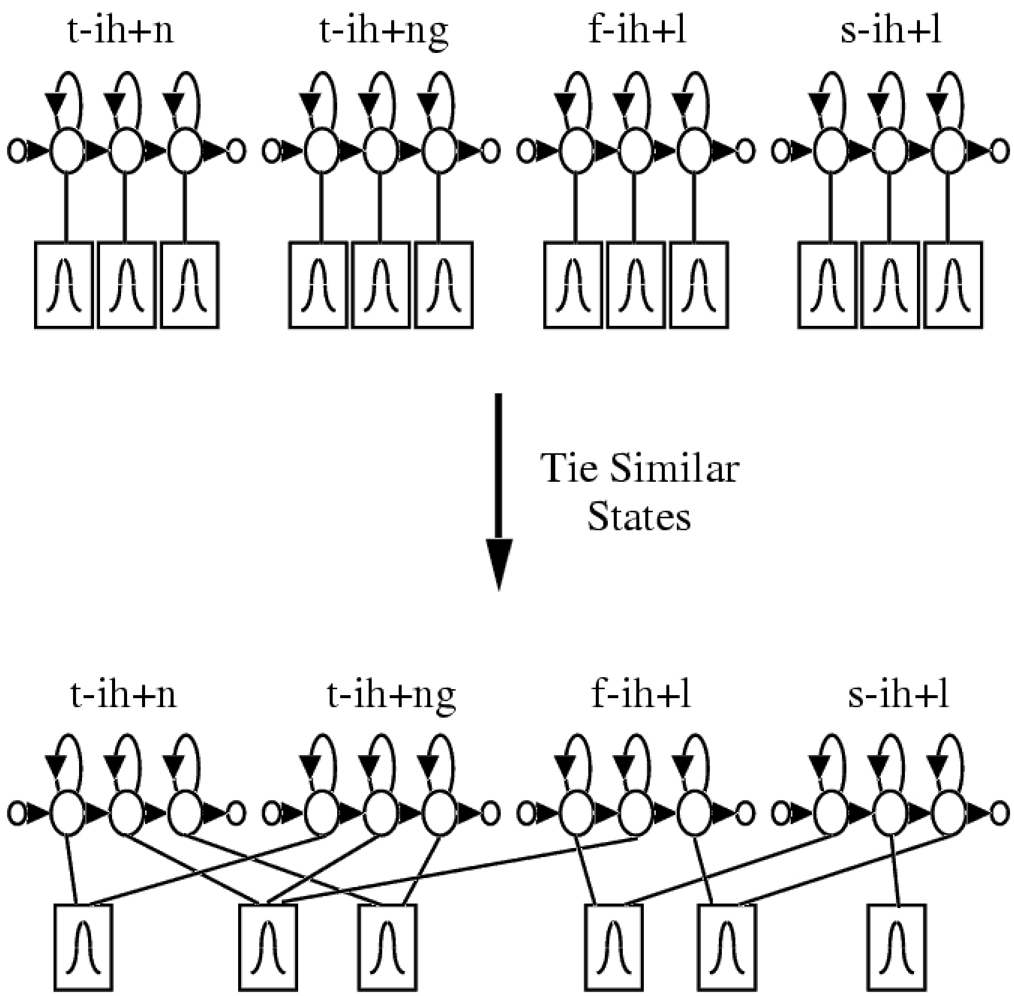
- Monophones
  - `sh iy  hh ae d  y uh r  d aa r k  s uw t`

- Triphones
  - Word internal triphones

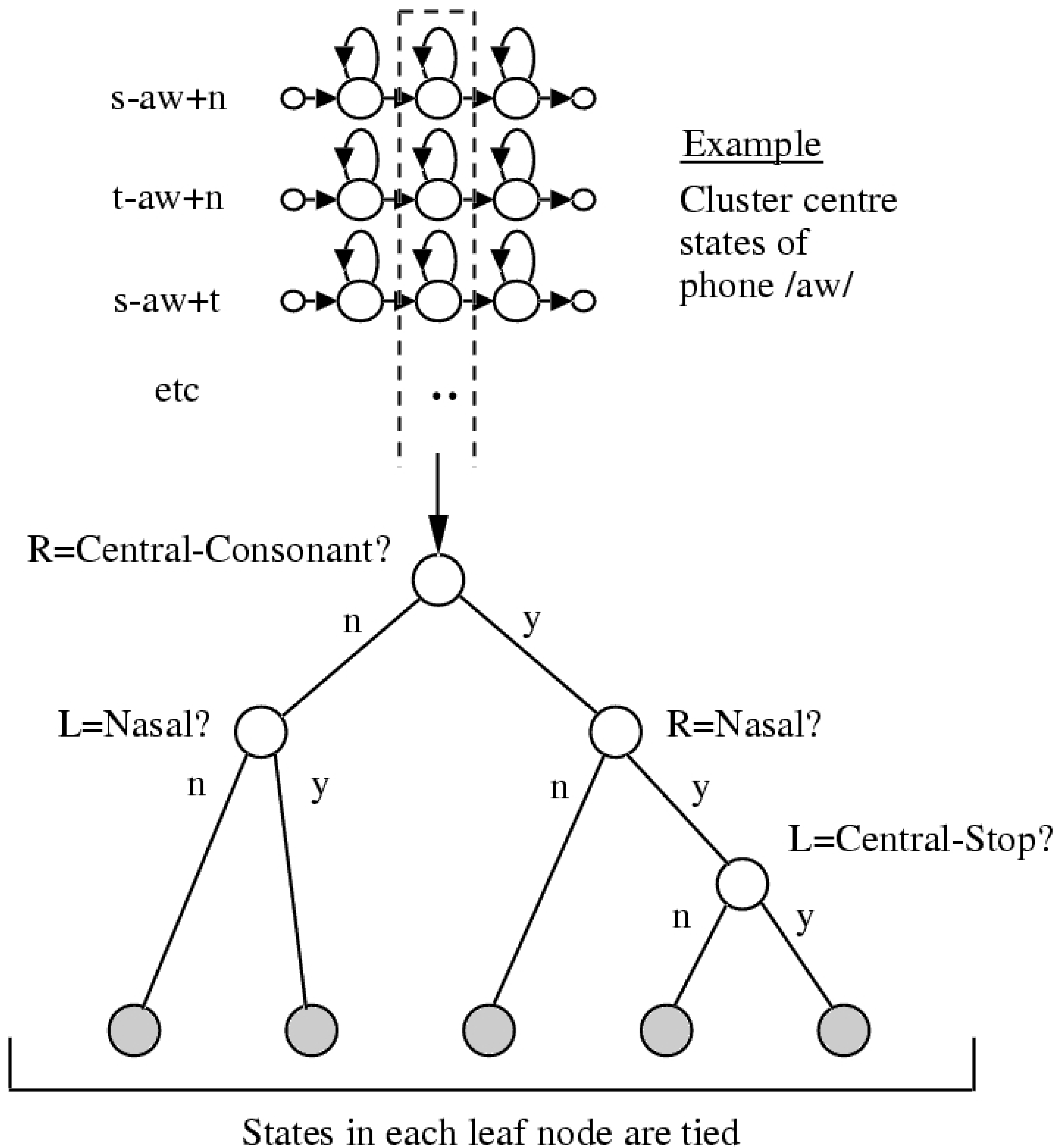
    `sh+iy sh–iy  hh+ae hh–ae+d ae–d  y+uh y–uh+r uh–r  d+aa d–aa+r aa–r+k r–k  s+uw s–uw+t uw–t`
  - Cross-word triphones

    `sil–sh+iy sh–iy+hh  iy–hh+ae hh–ae+d ae–d+y  d–y+uh y–uh+r uh–r+d r–d+aa d–aa+r aa–r+k r–k+s  k–s+uw s–uw+t uw–t+sil`

State Clustering



Decision Tree Based State Clustering



Contents

Language Models

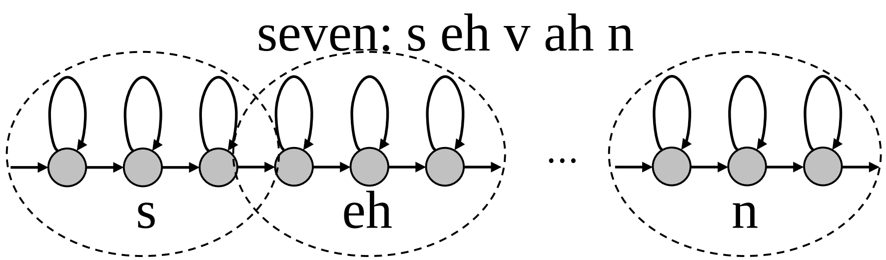
- Probability of an utterance u, where u is a word sequence $w^1, w^2, \cdots, w^n$.
  - $$\begin{aligned} p(u) &= p(w^1, w^2, \cdots, w^n) \\ &= p(w^1)p(w^2|w^1)p(w^3|w^1, w^2) \cdots p(w^n|w^1, w^2, \cdots, w^{n-1}) \\ &= \prod_i p\left(w^i \middle| w^1, w^2, \cdots, w^{i-1}\right) \\ &\approx \prod_i p\left(w^i \middle| w^{i-2}, w^{i-1}\right) && \text{; trigram} \\ &\approx \prod_i p\left(w^i \middle| w^{i-1}\right) && \text{; bigram} \\ &\approx \prod_i p\left(w^i\right) && \text{; unigram} \end{aligned}$$

Contents

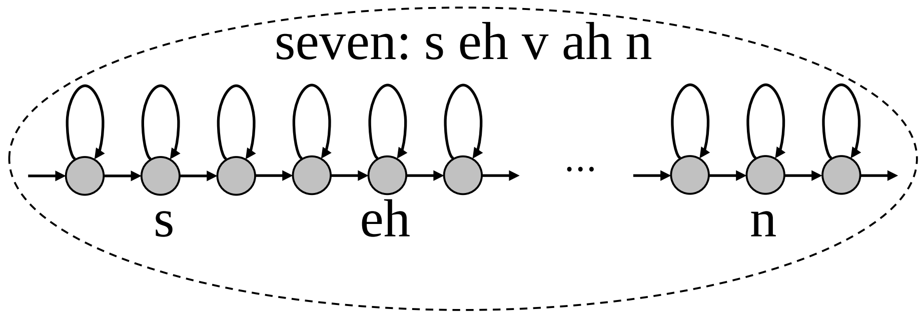
Isolated Word Recognition

- Find the most probable word $\hat{w}$ for a given input speech x (vector sequence).
  - $$\hat{w} = \arg\max_{w} p(w|x) = \arg\max_{w} \frac{p(w|x)p(w)}{p(x)} = \arg\max_{w} p(x|w)p(w)$$
  - $p(x|w)$: acoustic model probability
  - $p(w)$: language model probability (e.g., unigram)

Word HMM Construction

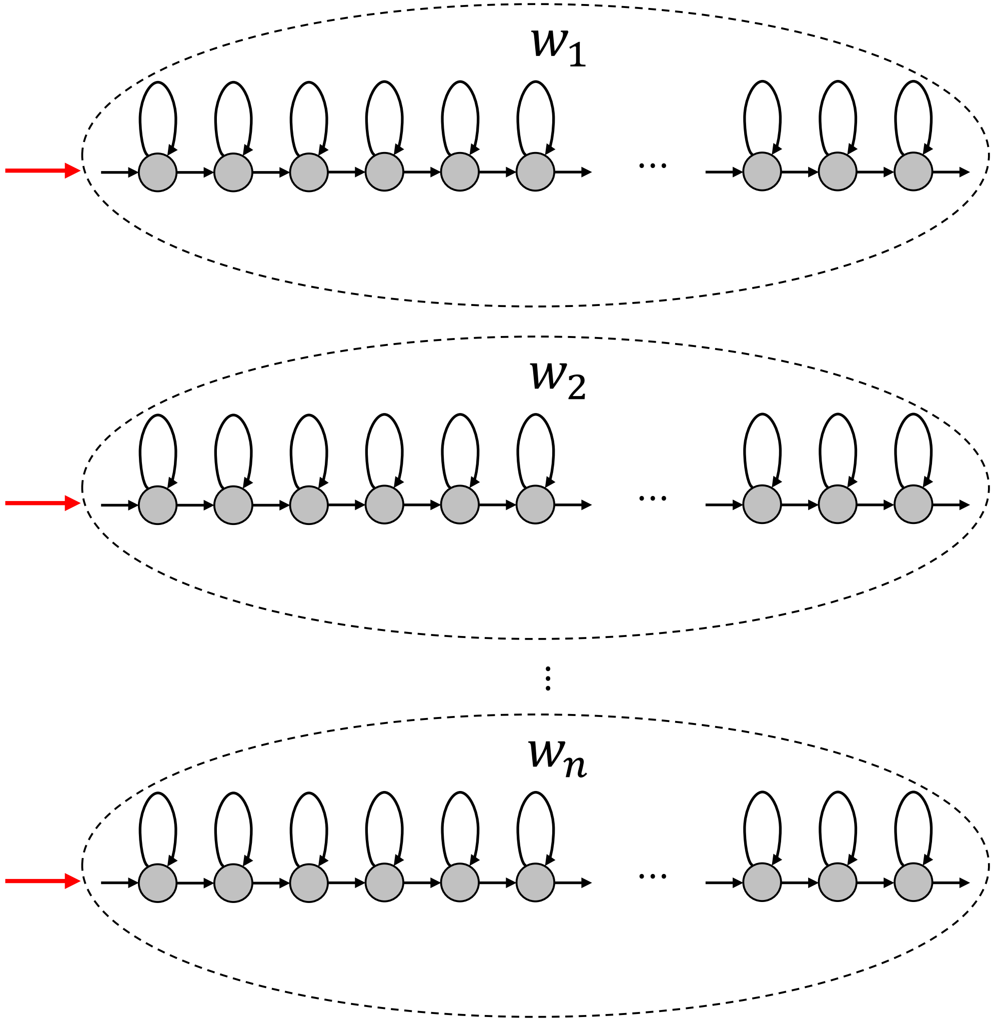


Word HMM Construction



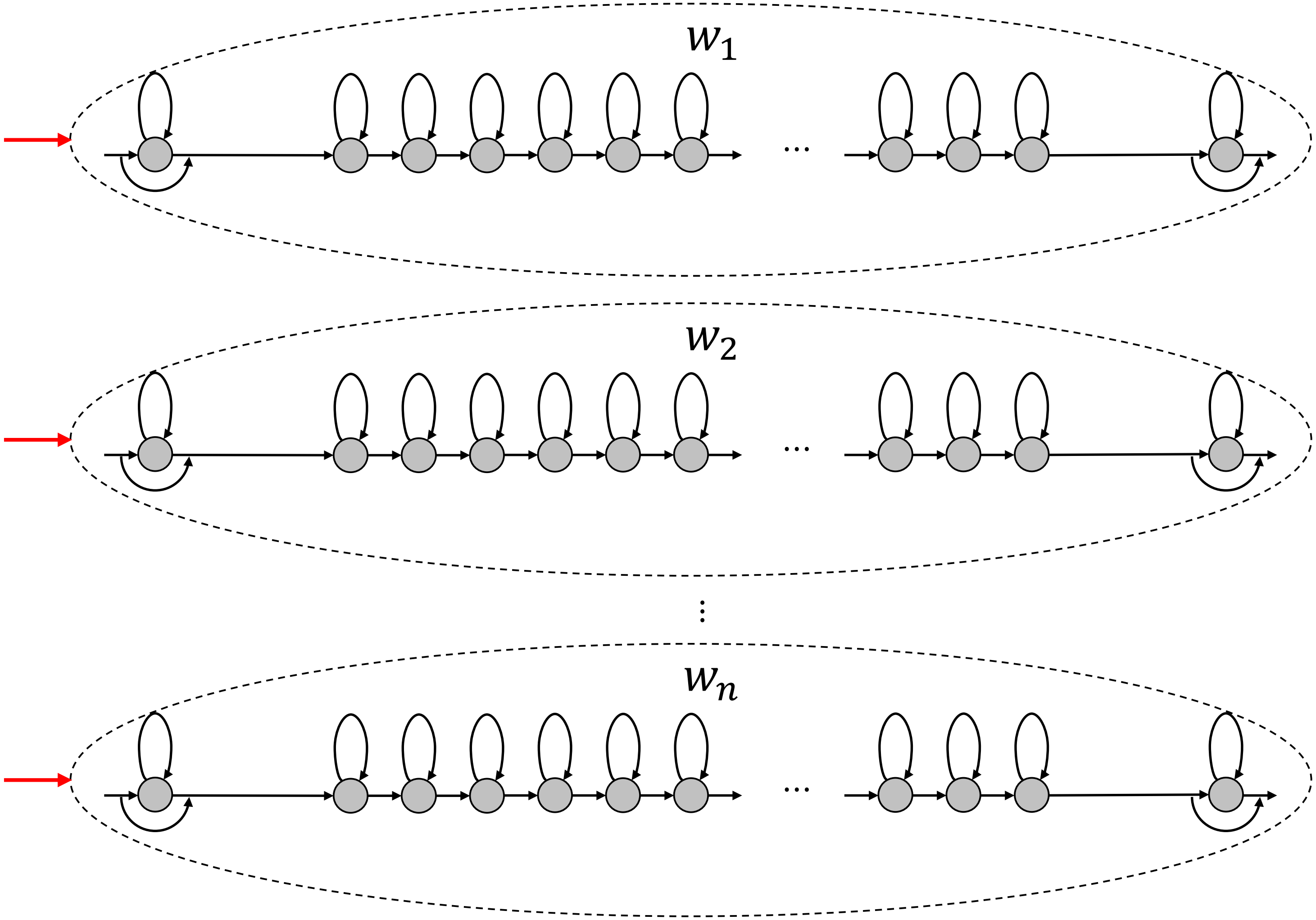
Isolated Word Recognition (Unigram)

$$\hat{w} = \arg\max_{w} p(w|x)$$
$$= \arg\max_{w} p(x|w)p(w)$$



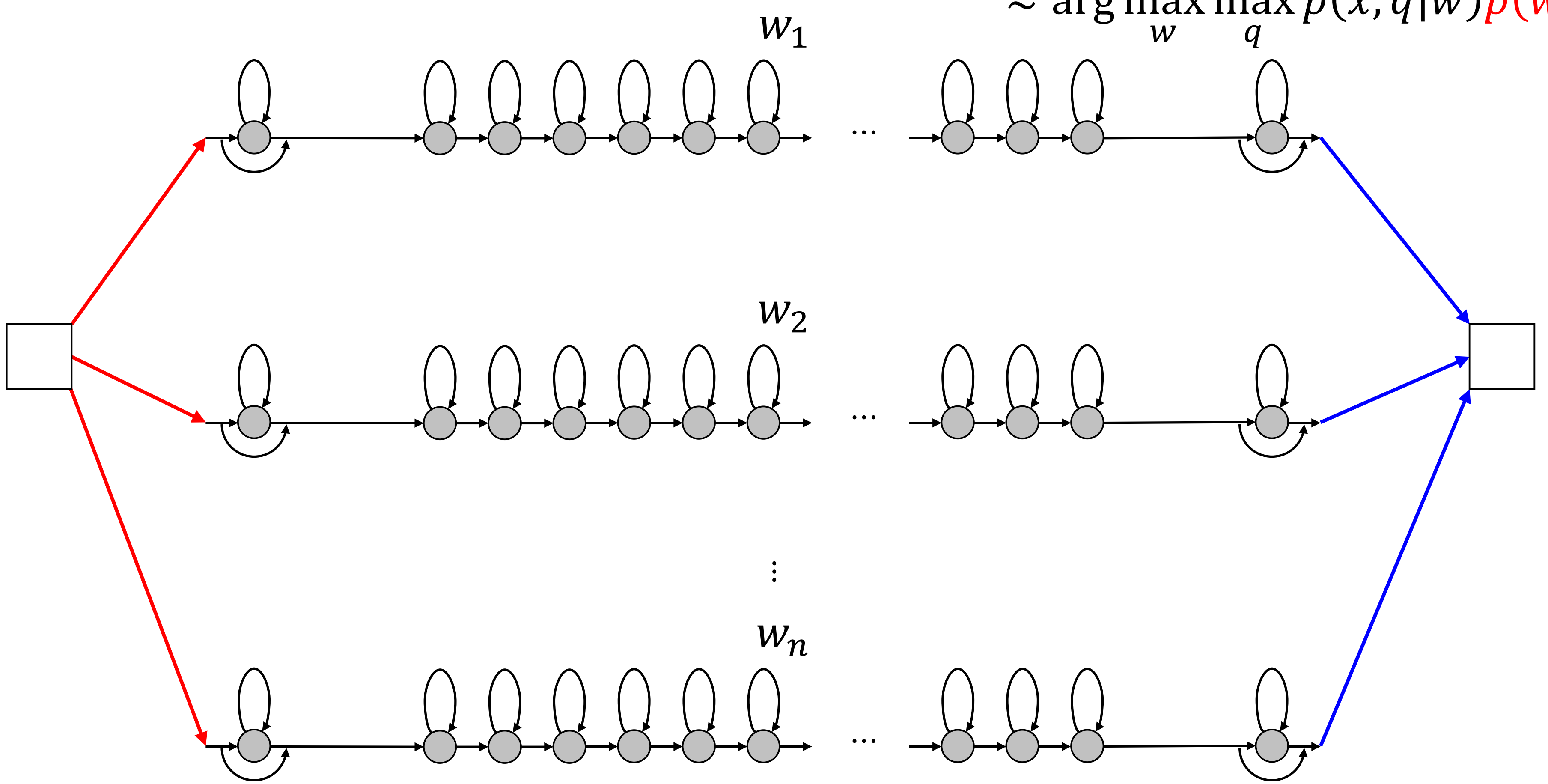
Isolated Word Recognition (Unigram)

$$\hat{w} = \arg\max_w p(w|x)$$
$$= \arg\max_w p(x|w)p(w)$$



Isolated Word Recognition (Unigram)

$$\begin{aligned}\hat{w} &= \arg\max_{w} p(w|x) \\ &= \arg\max_{w} p(x|w)p(w) \\ &\approx \arg\max_{w} \max_{q} p(x,q|w)p(w)\end{aligned}$$

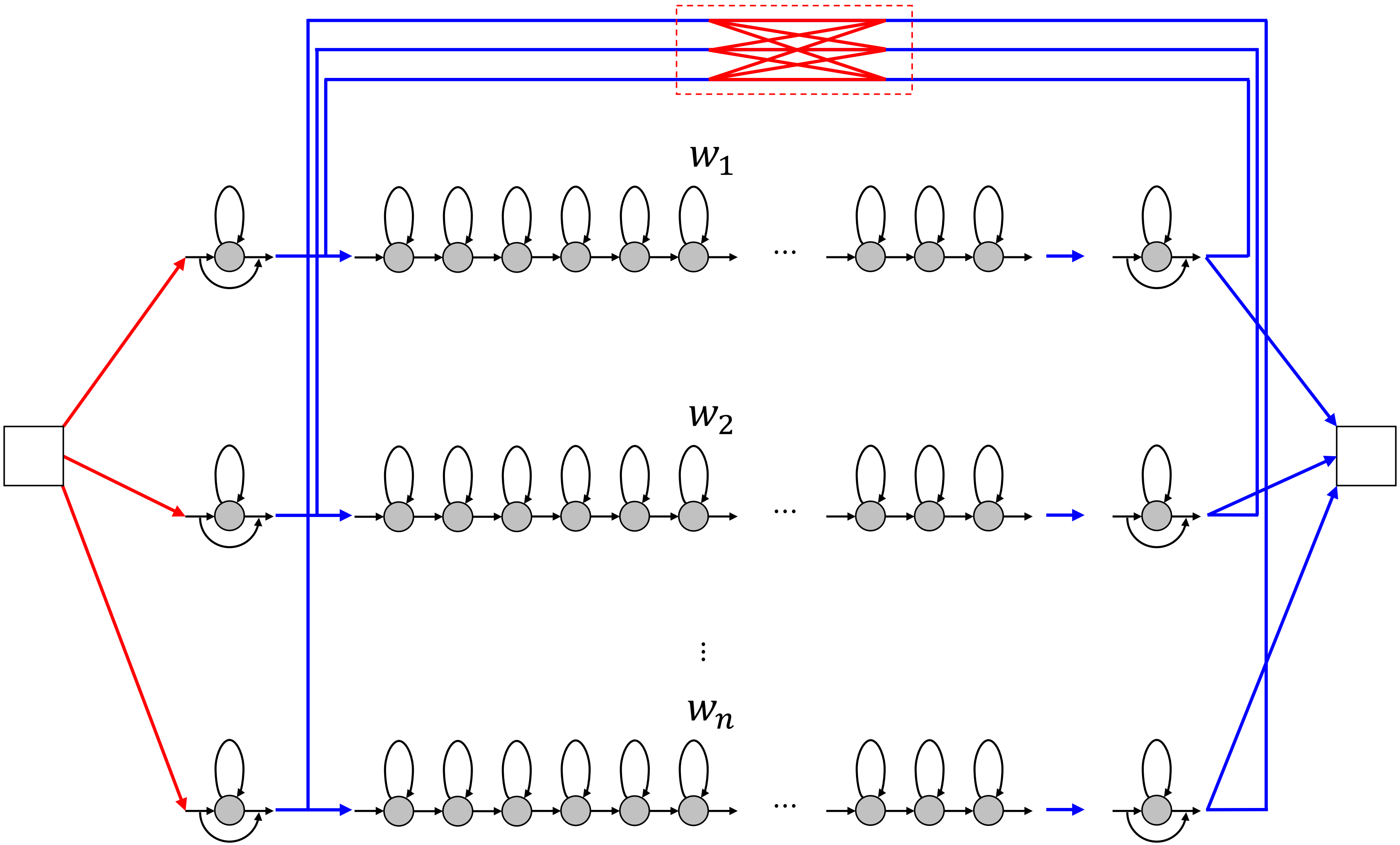


Contents

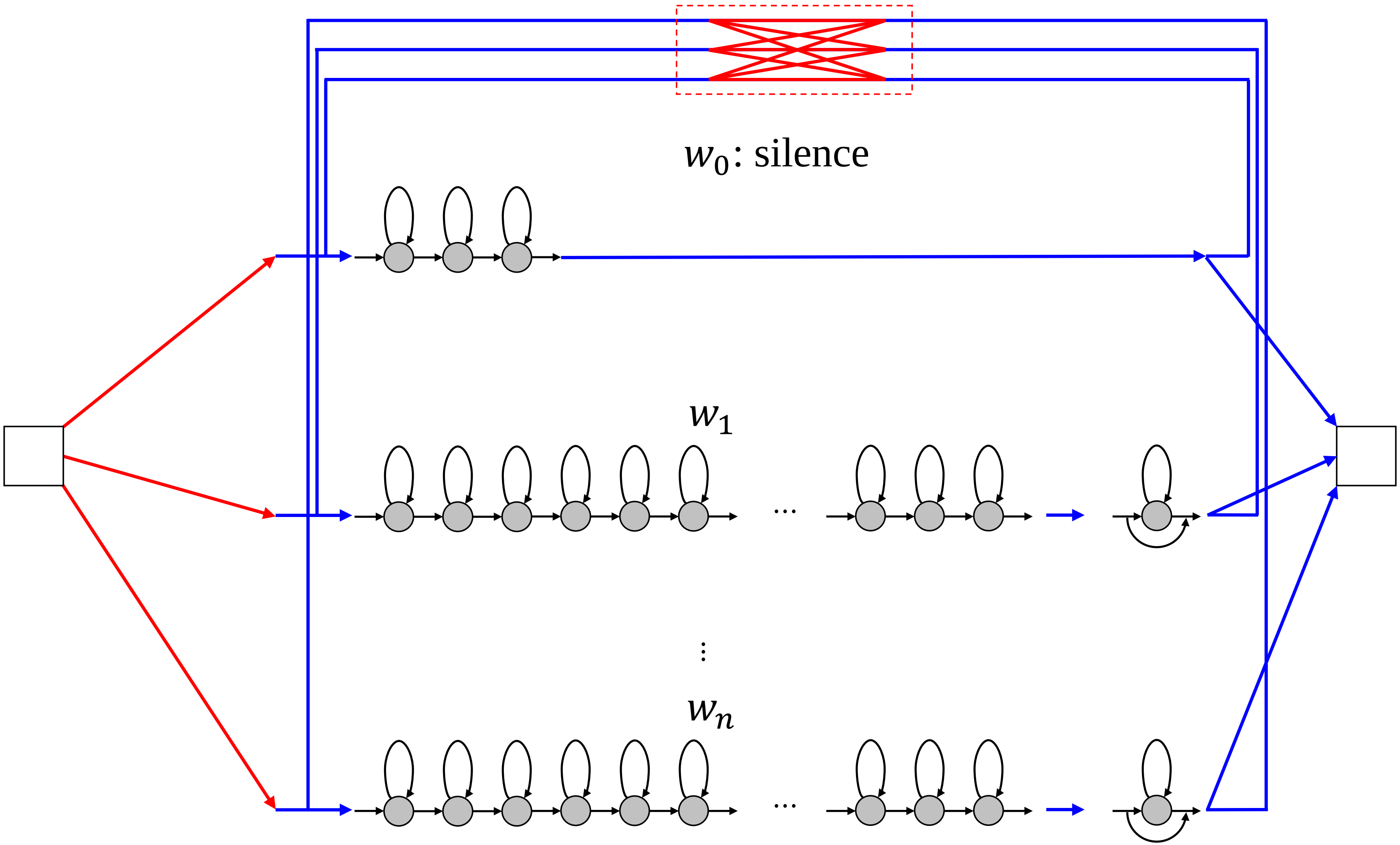
Continuous Speech Recognition

- Find the most probable word sequence $\hat{u}$ for a given input speech x (vector sequence).
  - $$\begin{aligned}\hat{u} &= \arg\max_u p(u|x) \\ &= \arg\max_u \frac{p(x|u)p(u)}{p(x)} \\ &= \arg\max_u p(x|u)p(u) \\ &= \arg\max_u \textstyle\sum_q p(x,q|u)\,p(u) \qquad ;\ q \text{ state sequence} \\ &\approx \arg\max_u \max_q p(x,q|u)\,p(u)\end{aligned}$$
  - $p(x,q|u)$: acoustic model probability
  - $p(u)$: language model probability (e.g., bigram)

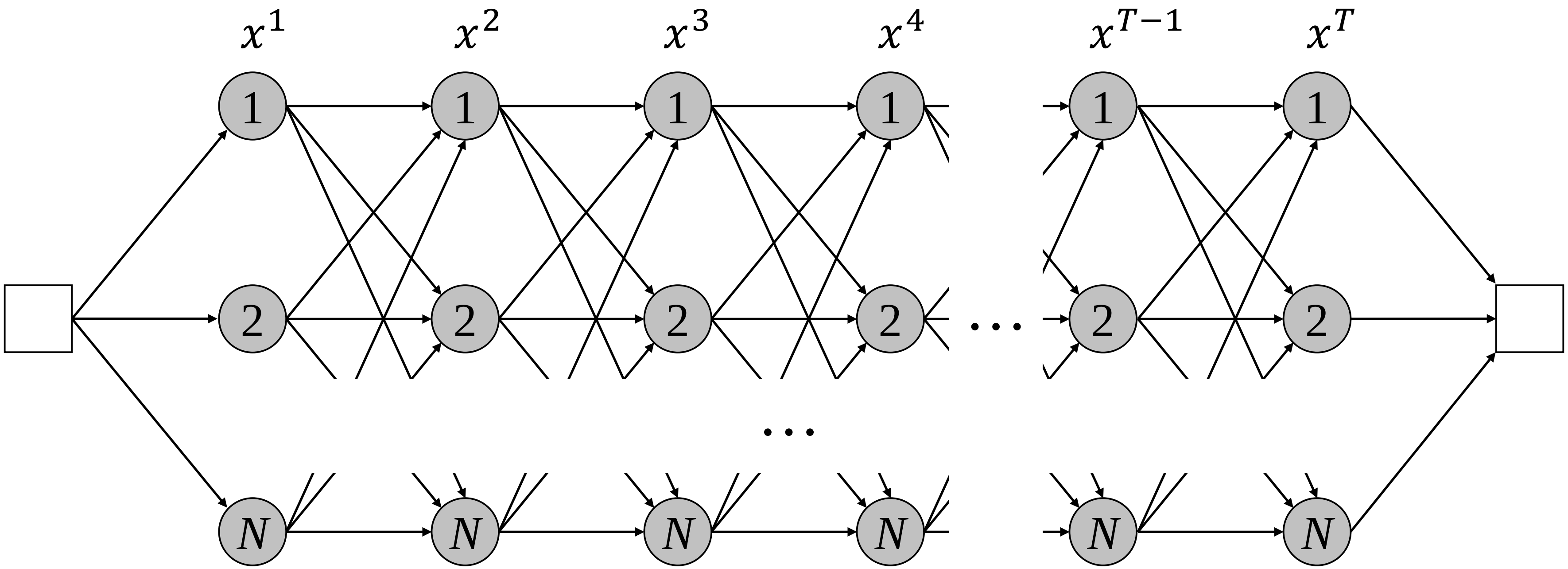
Utterance HMM Construction (Bigram)



Utterance HMM Construction (Bigram)



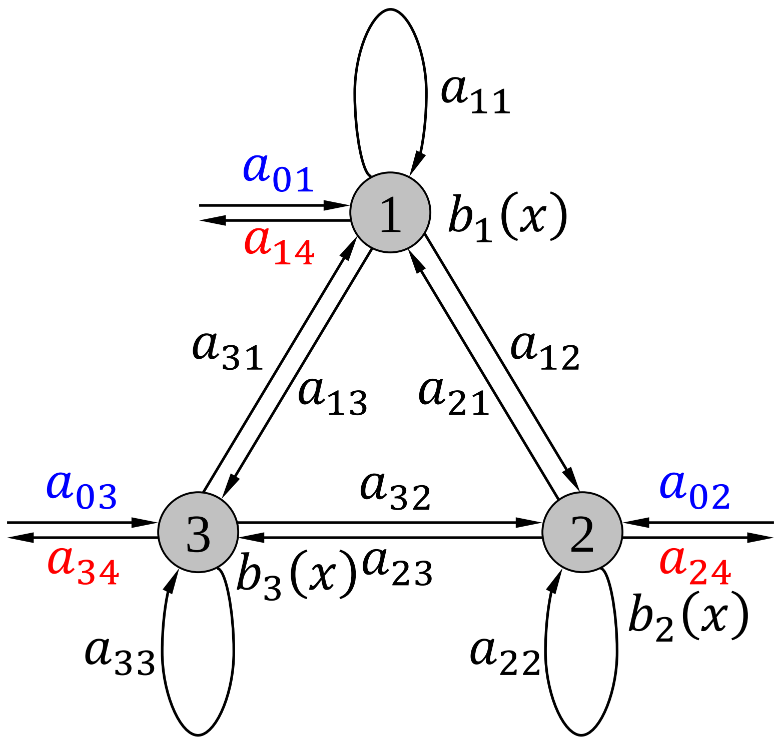
Continuous Speech Recognition (Bigram)



$$
\begin{aligned}
\hat{u} &= \arg\max_u p(u|x) \\
&= \arg\max_u \frac{p(x|u)p(u)}{p(x)} \\
&= \arg\max_u p(x|u)p(u) \\
&= \arg\max_u \textstyle\sum_q p(x, q|u)\, p(u) \\
&\approx \arg\max_u \max_q p(x, q|u)\, p(u)
\end{aligned}
$$

Three State HMM

- HMM $M = (a, b)$
  - Transition probability
    - $\pi = [\pi_1\ \pi_2\ \pi_3]$
    - $a = \begin{bmatrix} a_{00} & a_{01} & a_{02} & a_{03} & a_{04} \\ a_{10} & a_{11} & a_{12} & a_{13} & a_{14} \\ a_{20} & a_{21} & a_{22} & a_{23} & a_{24} \\ a_{30} & a_{31} & a_{32} & a_{33} & a_{34} \\ a_{40} & a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$
  - Observation probability
    - $b = \begin{bmatrix} b_1(1) & b_1(2) & & b_1(N_v) \\ b_2(1) & b_2(2) & \cdots & b_2(N_v) \\ b_3(1) & b_3(2) & & b_3(N_v) \end{bmatrix}$



Continuous Observations

- Discrete observation probability
  - $$b = \begin{bmatrix} b_1(1) & b_1(2) & & b_1(N_v) \\ b_2(1) & b_2(2) & \cdots & b_2(N_v) \\ b_3(1) & b_3(2) & & b_3(N_v) \end{bmatrix}$$

- Continuous observation probability
  - $$b_s(x) = \mathcal{N}(x|\mu_s, \sigma_s) = \frac{1}{\sqrt{2\pi}\sigma_s} e^{-\frac{1}{2}\frac{(x-\mu_s)^2}{\sigma_s^2}}$$
  - $$b_s(x) = \mathcal{N}(x|\mu_s, \Sigma_s) = \frac{1}{(2\pi)^{D/2}|\Sigma_s|^{1/2}} \exp\left(-\frac{1}{2}(x-\mu_s)^T \Sigma_s^{-1}(x-\mu_s)\right)$$
  - $$\begin{aligned} b_s(x) &= \sum_{g=1}^{G} c_{sg} \mathcal{N}\left(x\middle|\mu_{sg}, \Sigma_{sg}\right) \\ &= \sum_{g=1}^{G} c_{sg} \frac{1}{(2\pi)^{D/2}\left|\Sigma_{sg}\right|^{1/2}} \exp\left(-\frac{1}{2}\left(x-\mu_{sg}\right)^T \Sigma_{sg}^{-1}\left(x-\mu_{sg}\right)\right) \\ &\approx \sum_{g=1}^{G} c_{sg} \frac{1}{(2\pi)^{D/2} \prod_i \sigma_{sgi}} \exp\left(-\frac{1}{2}\sum_i \frac{\left(x_i-\mu_{sgi}\right)^2}{\sigma_{sgi}^2}\right) \end{aligned}$$

Implementation Issues

- Because of finite precision computation, $\log\alpha$, $\log\beta$, $\log\delta$, and $\log p(x|M)$ are used instead of α, β, δ, and $p(x|M)$, respectably.
  - e.g.,
    - e^{-1001}
    - $l_1 = \log e^{-1001} = -1001$
    - $l_2 = \log e^{-1002} = -1002$
    - $l_3 = \log(e^{-1001} + e^{-1002}) = \log\left(e^{l_1} + e^{l_2}\right)$
    - $l_3 = \log\left(e^{-1001}(e^{0} + e^{-1})\right) = \log e^{-1001} + \log(1 + e^{-1})$

- $$\begin{aligned}\log\textstyle\sum_i p_i &= \log(p_1 + p_2 + \cdots + p_n)\\ &= \log p_1\left(1 + \frac{p_2}{p_1} + \frac{p_3}{p_1} + \cdots + \frac{p_n}{p_1}\right)\\ &= \log p_1 + \log\left(1 + e^{\log\frac{p_2}{p_1}} + e^{\log\frac{p_3}{p_1}} + \cdots + e^{\log\frac{p_n}{p_1}}\right)\\ &= \log p_1 + \log\left(1 + e^{\log p_2 - \log p_1} + e^{\log p_3 - \log p_1} + \cdots + e^{\log p_n - \log p_1}\right)\\ &= l_1 + \log\left(1 + e^{l_2 - l_1} + e^{l_3 - l_1} + \cdots + e^{l_3 - l_1}\right) \quad ;\ l_i \equiv \log p_i\end{aligned}$$

Summary

- Introduction
- Feature Extraction
- Acoustic Models
- Language Models
- Decoding

Input Vector File Format

- Input vector sequence file

```
313 39
-1.589671e+01  4.339182e+00  1.678270e+00 -4.386323e-02  1.384665e-01 ...
-1.573894e+01  2.713936e+00  2.918963e+00  1.807250e+00 -1.625646e+00 ...
-1.589687e+01  1.784740e+00 -3.876205e-03  1.939704e+00  1.013269e+00 ...
-1.686176e+01  3.179346e+00  6.970119e-01  7.169858e-01 -1.466554e+00 ...
-1.602454e+01  4.159081e+00  2.404717e+00  1.300133e+00 -1.309275e+00 ...
-1.794216e+01 -1.226994e-01 -1.229748e+00  2.328833e-02  3.530599e+00 ...
-1.572281e+01  3.731576e+00 -4.482310e-01 -1.252083e-01  2.847649e+00 ...
-1.571102e+01  6.004687e+00  1.940033e+00 -9.302789e-01  1.905544e+00 ...
-1.866060e+01 -1.945088e-01 -9.612672e-01 -6.845327e-01 -4.278716e+00 ...
-1.790727e+01 -3.463200e-01 -2.204390e-01 -6.221546e-01 -3.650035e+00 ...
-1.687654e+01  1.089474e+00 -2.015056e+00  7.445039e-01  2.003541e+00 ...
-1.630165e+01  9.615828e-01 -2.796509e+00  2.851351e-02 -2.366324e+00 ...
-1.762898e+01  3.966002e-01 -6.038963e-01  5.937940e-01  7.313928e-02 ...
-1.687426e+01  1.015894e+00 -1.440334e+00  8.511196e-01 -3.999560e+00 ...
-1.656823e+01  2.526161e+00 -1.373639e+00  2.825755e+00 -3.559372e-01 ...
-1.605652e+01  2.725700e+00  1.645913e+00  4.513128e+00  1.367162e+00 ...
-1.615862e+01  2.757725e+00 -1.037673e-01  5.169404e-01  2.256959e+00 ...
-1.697908e+01  2.430228e+00  1.174574e+00 -6.864926e-01 -2.884347e+00 ...
-1.562105e+01  4.122203e+00  6.119420e-01  2.408284e+00  1.406704e+00 ...
-1.586861e+01  2.400448e+00 -2.723778e+00 -3.281356e+00  1.186900e+00 ...
-2.964692e+01 -4.892936e+00  5.048756e+00 -7.816375e-01  9.942081e+00 ...
-3.060667e+01 -5.355003e+00  5.724719e+00  7.978249e-01  1.216068e+01 ...
-1.542544e+01  2.674652e+00  3.692956e-01 -1.053609e+00  3.725806e+00 ...
-1.660411e+01  5.190681e+00  3.267094e-01  2.324215e+00  2.873489e+00 ...
-1.603844e+01  3.882752e+00 -1.272774e-01  6.141130e+00  3.787947e+00 ...
-1.589794e+01  1.520315e+00 -6.553339e-01  2.869384e+00 -2.616245e-01 ...
...
```

HMM File Format

- Single-Gaussian HMM

```
~h "ah"
<BEGINHMM>
<NUMSTATES> 5
<STATE> 2
<MEAN> 39
 1.898954e+000 -1.301708e+001 2.951807e-001 -8.873045e+000 -5.299952e+000 ...
<VARIANCE> 39
 1.374686e+001 2.792357e+001 3.375932e+001 3.855578e+001 5.125336e+001 ...
<GCONST> 1.185189e+002
<STATE> 3
 ...
<STATE> 4
 ...
<TRANSP> 5
 0.000000e+000 1.000000e+000 0.000000e+000 0.000000e+000 0.000000e+000
 0.000000e+000 6.985369e-001 3.014631e-001 0.000000e+000 0.000000e+000
 0.000000e+000 0.000000e+000 5.712691e-001 4.287309e-001 0.000000e+000
 0.000000e+000 0.000000e+000 0.000000e+000 5.327887e-001 4.672113e-001
 0.000000e+000 0.000000e+000 0.000000e+000 0.000000e+000 0.000000e+000
<ENDHMM>
~h "ao"
<BEGINHMM>
 ...
<ENDHMM>
...
```

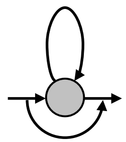
HMM File Format

- Two-Gaussian HMM

```
~h "ah"
<BEGINHMM>
<NUMSTATES> 5
<STATE> 2
<NUMMIXES> 2
<MIXTURE> 1 4.817315e-001
<MEAN> 39
 4.137055e+000 -1.180742e+001 1.235130e+000 -6.246143e+000 -5.400127e+000 ...
<VARIANCE> 39
 9.940362e+000 2.234269e+001 3.181495e+001 3.140755e+001 3.038879e+001 ...
<GCONST> 1.134534e+002
<MIXTURE> 2 5.182614e-001
<MEAN> 39
 7.230198e-002 -1.516407e+001 -2.030157e+000 -1.170948e+001 -3.230822e+000 ...
<VARIANCE> 39
 9.100752e+000 2.617574e+001 3.306291e+001 3.100306e+001 7.574311e+001 ...
<GCONST> 1.088633e+002
<STATE> 3
 ...
<STATE> 4
 ...
<TRANSP> 5
 ...
<ENDHMM>
...
```

HMM File Format

- Optional silence HMM



```
~h "sp"
<BEGINHMM>
<NUMSTATES> 3
<STATE> 2
<NUMMIXES> 2
<MIXTURE> 1 5.687151e-001
<MEAN> 39
 -1.528916e+001 1.884770e+000 -1.786322e-001 9.084788e-001 -2.541062e-001 ...
<VARIANCE> 39
 3.127717e+000 3.337751e+000 4.364497e+000 6.843961e+000 9.882758e+000 ...
<GCONST> 6.342905e+001
<MIXTURE> 2 4.312517e-001
<MEAN> 39
 -1.353393e+001 5.515828e-001 -1.442452e+000 3.601370e-001 -1.042004e+000 ...
<VARIANCE> 39
 9.201511e+000 1.160456e+001 1.037773e+001 9.865545e+000 1.413276e+001 ...
<GCONST> 8.848967e+001
<TRANSP> 3
 0.000000e+000 8.050888e-002 9.194912e-001
 0.000000e+000 9.276201e-001 7.237989e-002
 0.000000e+000 0.000000e+000 0.000000e+000
<ENDHMM>
```

HMM in Header File Format

- HMM in header file format for C programming

```
#define N_STATE      3
#define N_PDF        10
#define N_DIMENSION  39

typedef struct {
  float weight;
  float mean[N_DIMENSION];
  float var[N_DIMENSION];
} pdfType;

typedef struct {
  pdfType pdf[N_PDF];
} stateType;

typedef struct {
  char *name;
  float tp[N_STATE+2][N_STATE+2];
  stateType state[N_STATE];
} hmmType;
```

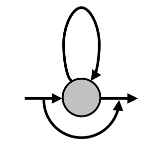
HMM in Header File Format

- HMM in header file format for C programming

```
hmmType phones[] = {
  { "f", // HMM
    { // transition probability
      { 0.000000e+000, 1.000000e+000, 0.000000e+000, 0.000000e+000, 0.000000e+000 },
      { 0.000000e+000, 8.519424e-001, 1.480576e-001, 0.000000e+000, 0.000000e+000 },
      { 0.000000e+000, 0.000000e+000, 7.039050e-001, 2.960950e-001, 0.000000e+000 },
      { 0.000000e+000, 0.000000e+000, 0.000000e+000, 5.744837e-001, 4.255163e-001 },
      { 0.000000e+000, 0.000000e+000, 0.000000e+000, 0.000000e+000, 0.000000e+000 }
    },
    {
      {{// state 1
        { // pdf 1
          8.379531e-002,
          { -1.100132e+001, -1.507629e+000, 5.286411e+000, 5.901514e+000, ... },
          { 2.583579e+001, 1.714888e+001, 1.768794e+001, 1.732637e+001, ... }
        },
        { // pdf 2
          ...
        },
        ...
      }},
      {{// state 2
        ...
      }}
      ...
    }
  },
  { "k", // HMM
    ...
  }
  ...
```

HMM in Header File Format

- HMM in header file format for C programming



```
  ...
  { "sp", // HMM
    { // transition probability
      { 0.000000e+000, 2.385641e-001, 7.614358e-001 },
      { 0.000000e+000, 9.152609e-001, 8.473914e-002 },
      { 0.000000e+000, 0.000000e+000, 0.000000e+000 }
    },
    {
      {{// state 1
        { // pdf 1
          1.120568e-001,
          { -1.508647e+001, 1.690120e+000, -3.829488e-001, 6.419236e-001, ... },
          { 3.735557e+000, 4.400073e+000, 6.065806e+000, 7.459801e+000, ... }
        },
        { // pdf 2
          ...
        },
        ...
      }}
    }
  },
};
```

Pronunciation Dictionary

- Pronunciation dictionary

```
<s>     sil
eight   ey t
five    f ay v
four    f ao r
nine    n ay n
oh      ow
one     w ah n
seven   s eh v ah n
six     s ih k s
three   th r iy
two     t uw
zero    z ih r ow
zero    z iy r ow
```

Language Models

- Unigram

```
<s>     0.990000
eight   0.000925
five    0.000890
four    0.000886
nine    0.000905
oh      0.000968
one     0.000905
seven   0.000869
six     0.000939
three   0.000883
two     0.000941
zero    0.000889
```

- Bigram

```
<s>     eight   0.012084
<s>     five    0.011881
<s>     four    0.009139
<s>     nine    0.011474
<s>     oh      0.012591
<s>     one     0.010967
<s>     seven   0.010967
<s>     six     0.011779
<s>     three   0.010865
<s>     two     0.013201
<s>     zero    0.010053
eight   <s>     0.012287
eight   eight   0.005991
eight   five    0.005788
eight   four    0.006600
eight   nine    0.007616
eight   oh      0.006397
eight   one     0.005585
eight   seven   0.005483
eight   six     0.005991
eight   three   0.005890
eight   two     0.006803
eight   zero    0.006499
five    <s>     0.013708
five    eight   0.005788
five    five    0.005686
...
zero    zero    0.013911
```

Label Format

- Label format (reference)

```
#!MLF!#
"tst/f/ak/1237743.lab"
one
two
three
seven
seven
four
three
.
"tst/f/ak/1393387.lab"
one
three
nine
three
three
eight
seven
.
"tst/f/ak/276317o.lab"
two
seven
six
three
one
seven
oh
.
```

Label Format

- Label format (recognized)

```
#!MLF!#
"tst/f/ak/1237743.rec"
one
two
three
seven
seven
four
three
.
"tst/f/ak/1393387.rec"
one
three
nine
three
three
eight
seven
.
"tst/f/ak/276317o.rec"
two
seven
six
three
one
seven
oh
.
```

Confusion Matrix

- Confusion matrix

```
HResults -p -I reference vocabulary recognized

====================== HTK Results Analysis =======================
  Date: Mon Jan 1 00:00:00 2014
  Ref : reference
  Rec : recognized
------------------------ Overall Results --------------------------
SENT: %Correct=87.52 [H=1087, S=155, N=1242]
WORD: %Corr=99.82, Acc=97.98 [H=8678, D=4, S=12, I=160, N=8694]
------------------------ Confusion Matrix -------------------------
       z   o   o   t   t   f   f   s   s   e   n
       e   h   n   w   h   o   i   i   e   i   i
       r       e   o   r   u   v   x   v   g   n
       o               e   r   e       e   h   e
                       e               n   t      Del [ %c / %e]
zero  815  0   0   0   0   0   0   0   0   0   0    0
  oh   0  744  0   1   0   1   0   0   0   0   2    2 [99.5/0.0]
 one   0   0  809  0   0   0   0   0   0   0   1    0 [99.9/0.0]
 two   0   0   0  803  1   0   0   0   0   0   0    1 [99.9/0.0]
thre   0   0   0   2  812  0   0   0   0   0   0    0 [99.8/0.0]
four   0   0   0   0   0  783  1   0   0   0   0    0 [99.9/0.0]
five   0   0   0   0   0   0  784  0   0   0   0    0
 six   0   0   0   0   0   0   0  800  1   0   0    0 [99.9/0.0]
seve   0   0   1   0   0   0   0   0  791  0   0    0 [99.9/0.0]
eigh   0   1   0   0   0   0   0   0   0  824  0    1 [99.9/0.0]
nine   0   0   0   0   0   0   0   0   0   0  713   0
Ins    0  97   5   8   0   0   1   0   0  44   5
===================================================================
```