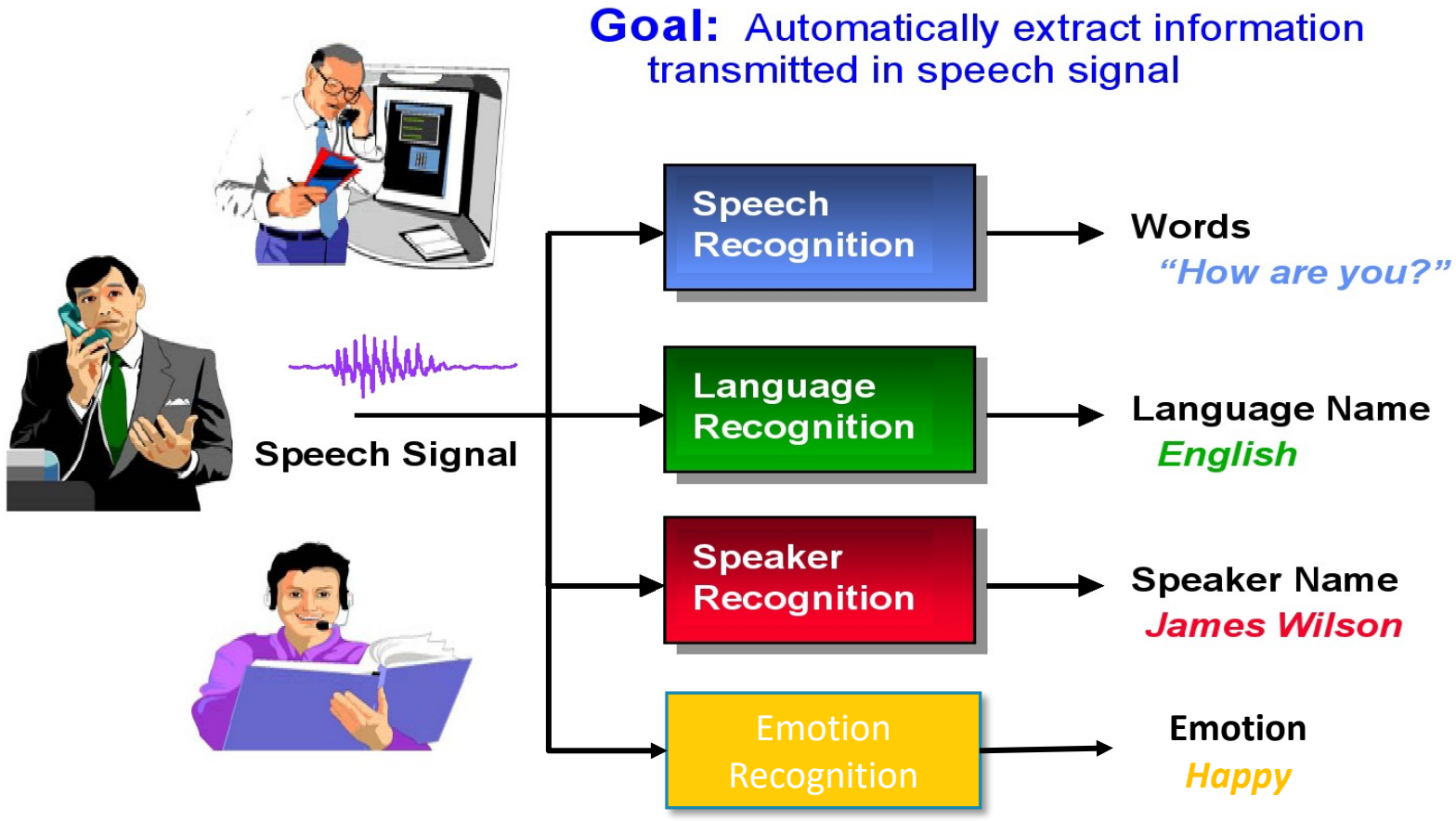
Introduction to Speech Recognition

Yuan-Fu Liao

National Taipei University of Technology

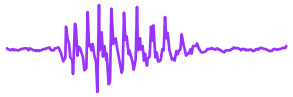
Broad Objectives of Speech Recognition for Machines



Source : Reynolds et. al

Speech Recognition

Goal: Automatically extract the string of words spoken from the speech signal



Speech Signal

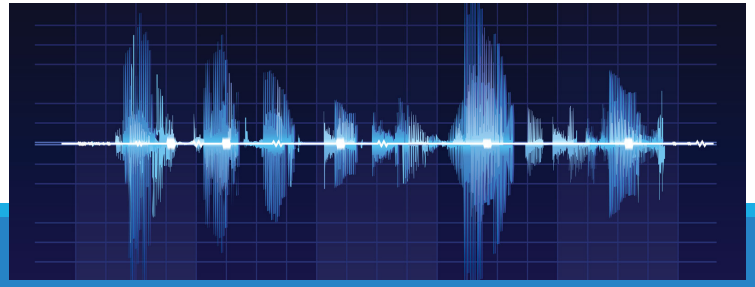
Speech Recognition

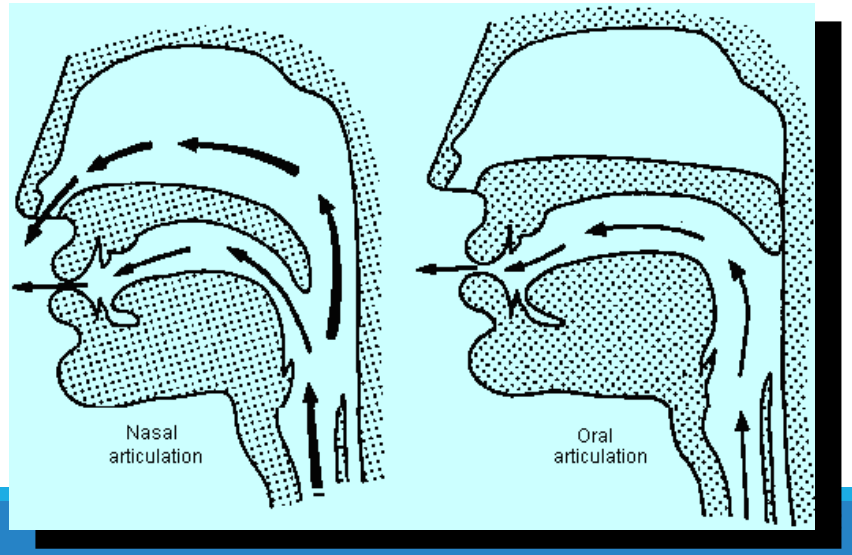
Words

"How are you?"

How is SPEECH produced?

⇒ Characteristics of Acoustic Signal





Speech Recognition

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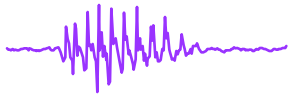


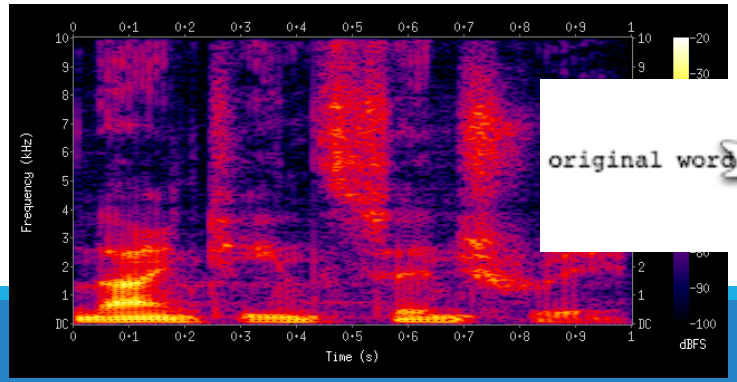
Speech Signal

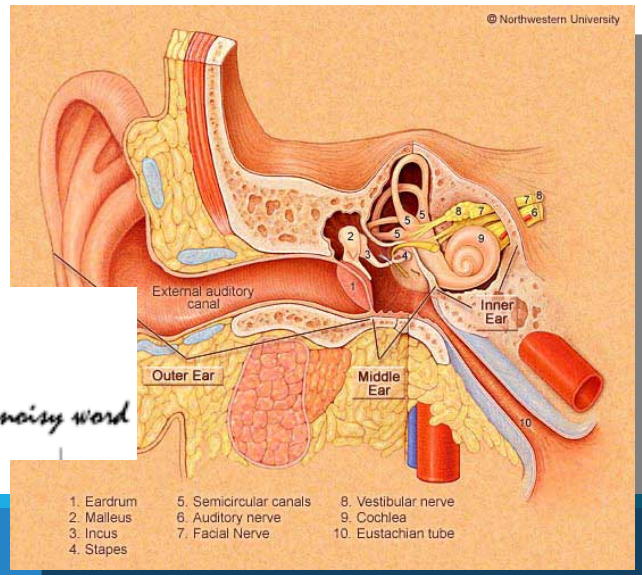
Speech Recognition

Words

"How are you?"

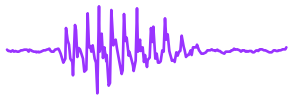
How is SPEECH perceived?
=> Important Features





Speech Recognition

Goal: Automatically extract the string of words spoken from the speech signal



Speech Signal

Speech Recognition

Words

"How are you?"

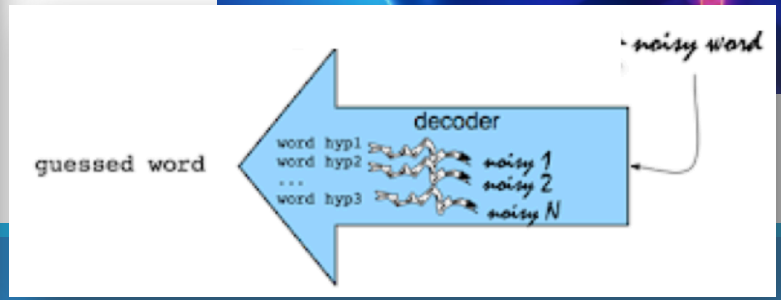
What Sentence is Spoken? => Language Model

Alice was beginning to get very tired of sitting by her sister on the bank, and of having nothing to do: once or twice she had peeped into the book her sister was reading, but it had no pictures or conversations in it, 'and what is the use of a book,' thought Alice 'without pictures or conversation?'

$P(w_{i+1}=\text{of} \mid w_i=\text{tired}) = 1$
$P(w_{i+1}=\text{of} \mid w_i=\text{use}) = 1$
$P(w_{i+1}=\text{sister} \mid w_i=\text{her}) = 1$
$P(w_{i+1}=\text{beginning} \mid w_i=\text{was}) = 1/2$
$P(w_{i+1}=\text{reading} \mid w_i=\text{was}) = 1/2$

$P(w_{i+1}=\text{bank} \mid w_i=\text{the}) = 1/3$
$P(w_{i+1}=\text{book} \mid w_i=\text{the}) = 1/3$
$P(w_{i+1}=\text{use} \mid w_i=\text{the}) = 1/3$

$$P(X|Y) = \frac{P(X,Y)}{P(Y)}$$



Aim of Automatic Speech Recognition

Find the most likely sentence (word sequence) $\boldsymbol{W}$, which transcribes the speech audio $\boldsymbol{A}$:

$$\widehat{\boldsymbol{W}} = \underset{\boldsymbol{W}}{\operatorname{argmax}}\, P(\boldsymbol{W}|\boldsymbol{A}) = \underset{\boldsymbol{W}}{\operatorname{argmax}}\, P(\boldsymbol{A}|\boldsymbol{W})P(\boldsymbol{W})$$

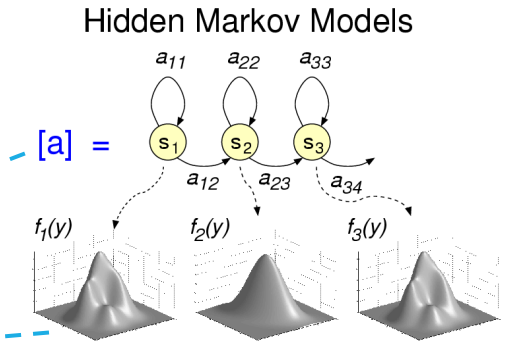
- Acoustic model $P(\boldsymbol{A}|\boldsymbol{W})$
- Language model $P(\boldsymbol{W})$

Training: find parameters for acoustic and language model separately

- Speech Corpus: speech waveform and human-annotated transcriptions
- Language model: with extra data (prefer daily expressions corpus for spontaneous speech)

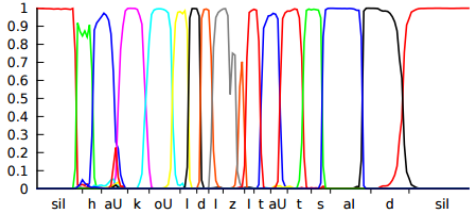
Automatic Speech Recognition

$$\widehat{\boldsymbol{W}} = \underset{\boldsymbol{W}}{\operatorname{argmax}}\, P(\boldsymbol{W}|\boldsymbol{O}) = \underset{\boldsymbol{W}}{\operatorname{argmax}}\, P(\boldsymbol{A}|\boldsymbol{O})P(\boldsymbol{O}|\boldsymbol{Q})P(\boldsymbol{Q}|\boldsymbol{L})P(\boldsymbol{L}|\boldsymbol{W})P(\boldsymbol{W})$$



$P(\boldsymbol{A}|\boldsymbol{O})$ | $P(\boldsymbol{O}|\boldsymbol{Q})$ | $P(\boldsymbol{Q}|\boldsymbol{L})$ | $P(\boldsymbol{L}|\boldsymbol{W})$ | $P(\boldsymbol{W})$

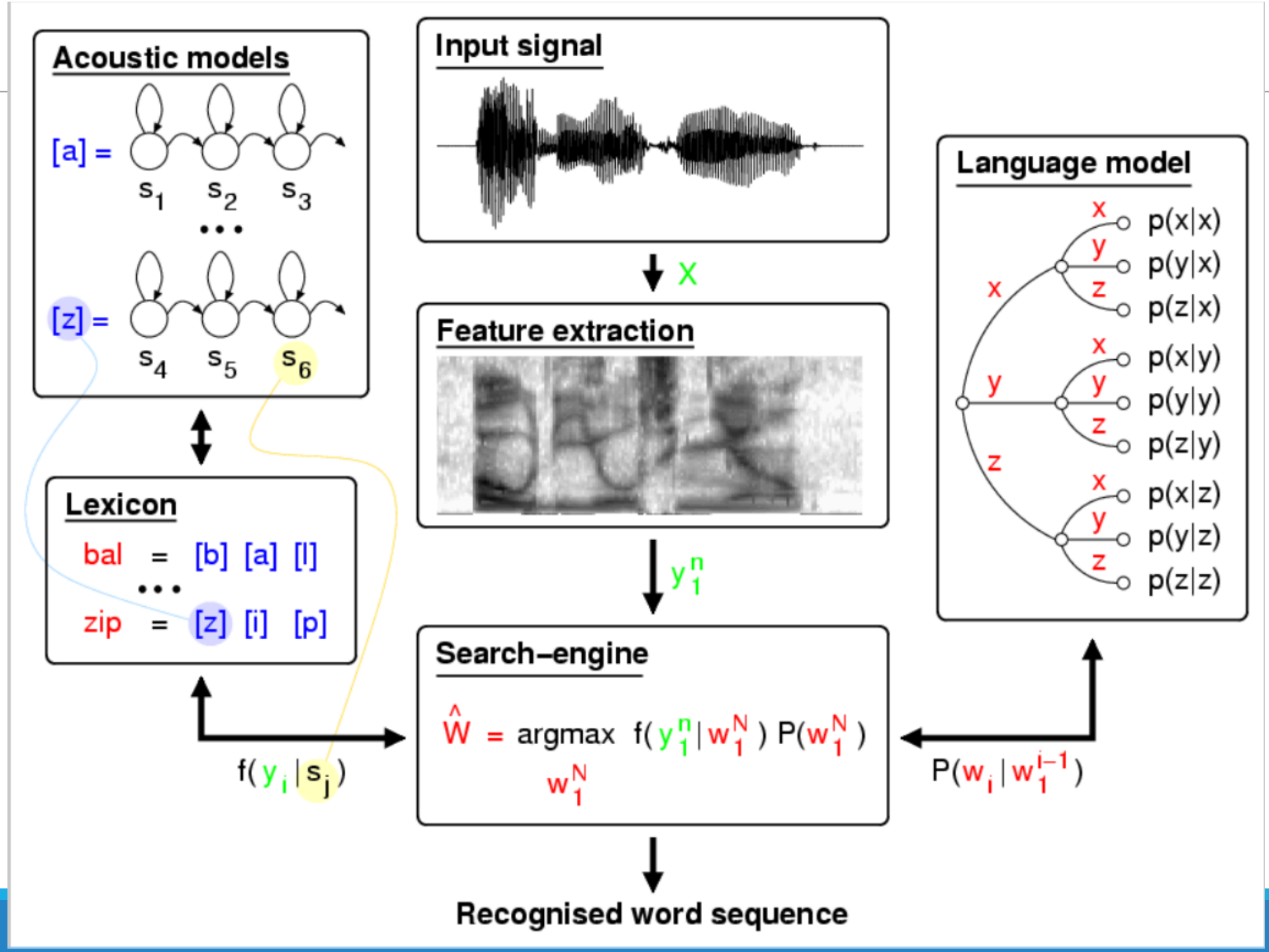
Feature Extraction → Frame Classification → Sequence Model → Lexicon Model → Language Model

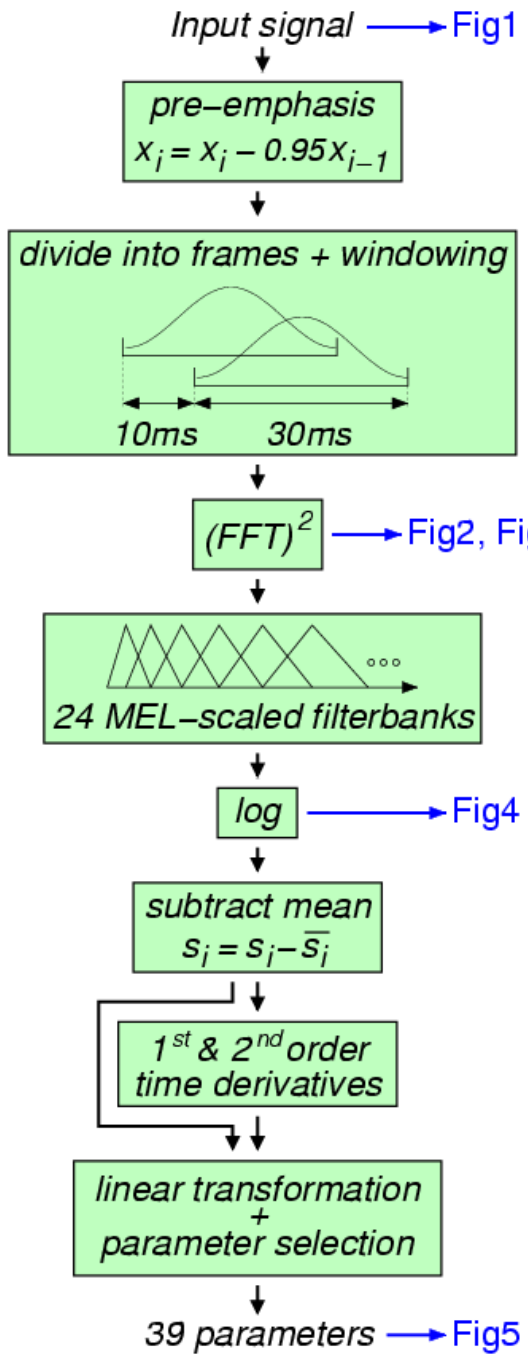


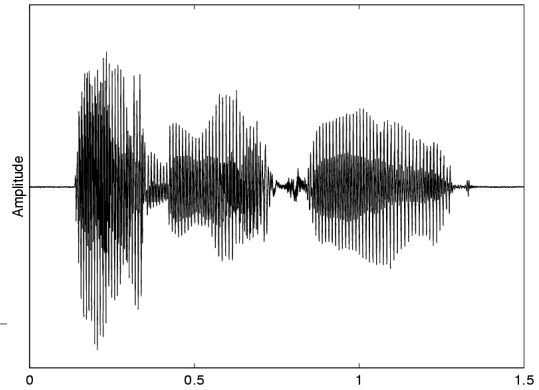
t ah m aa t ow

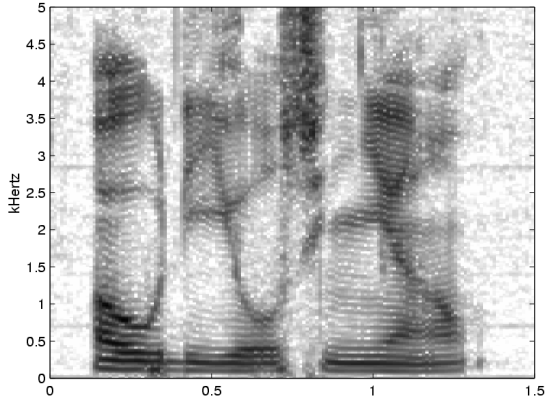
$\boldsymbol{A}$	$\boldsymbol{O}$	$\boldsymbol{Q}$	$\boldsymbol{L}$	$\boldsymbol{W}$	
Speech Audio	Feature Frames	Sequence States	Phonemes	Words	Sentence

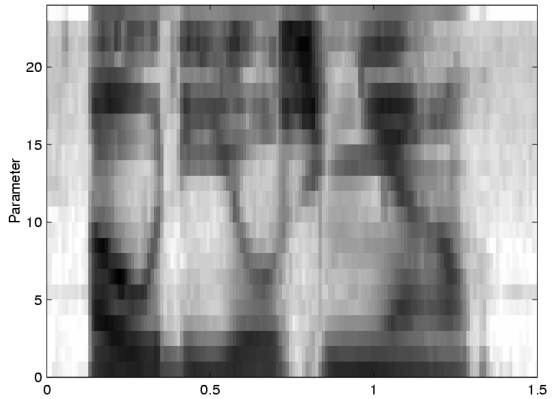
Automatic Speech Recognition: Short Introduction

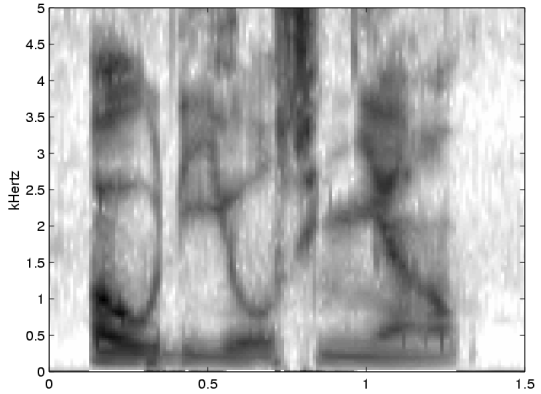


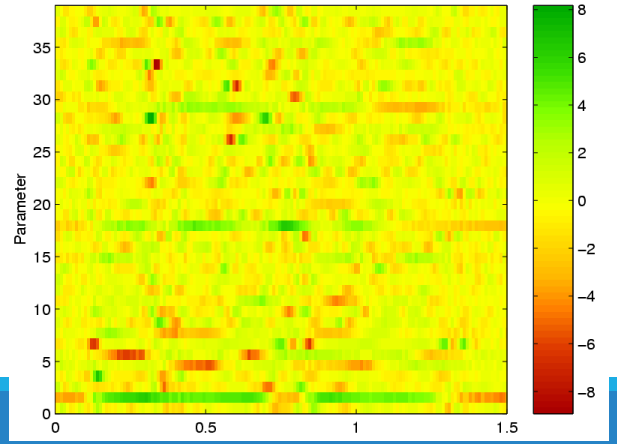

Input signal
Fig1
pre–emphasis
$x_i = x_i - 0.95x_{i-1}$
divide into frames + windowing
10ms
30ms
$(FFT)^2$
Fig2, Fig3
24 MEL–scaled filterbanks
log
Fig4
subtract mean
$s_i = s_i - \bar{s}_i$
1st & 2nd order time derivatives
linear transformation + parameter selection
39 parameters
Fig5


Amplitude

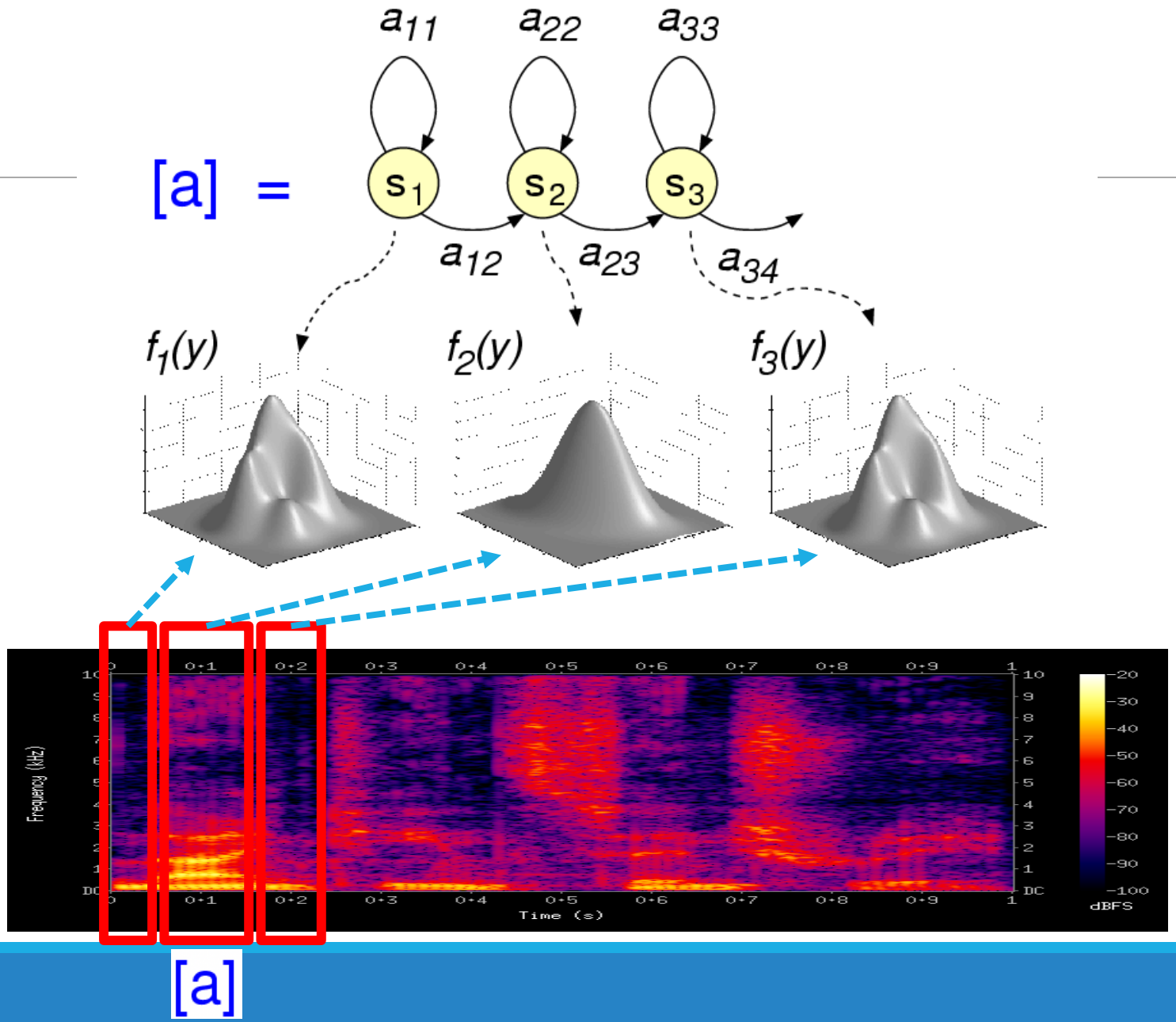

kHertz

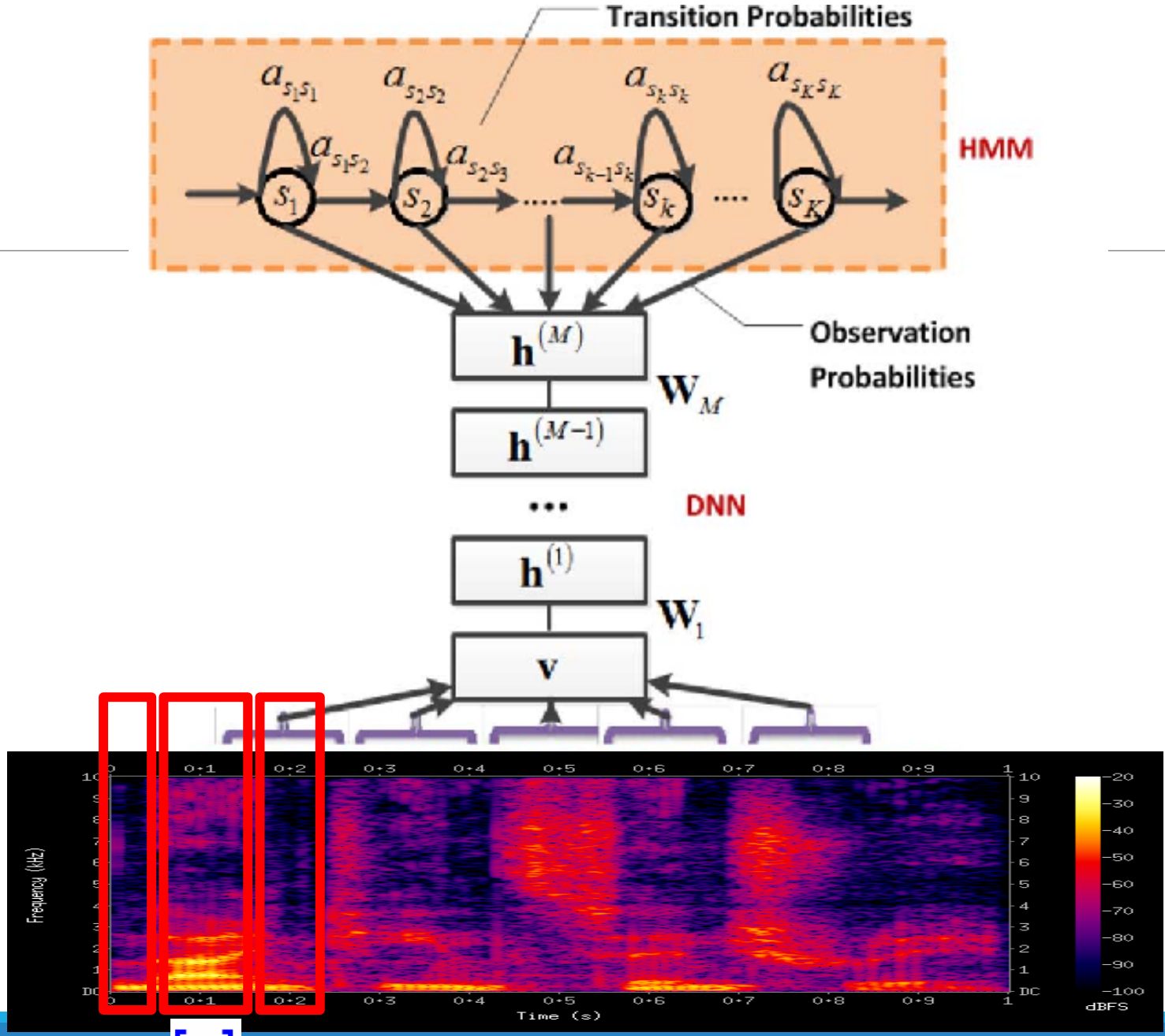

Parameter


kHertz


Parameter

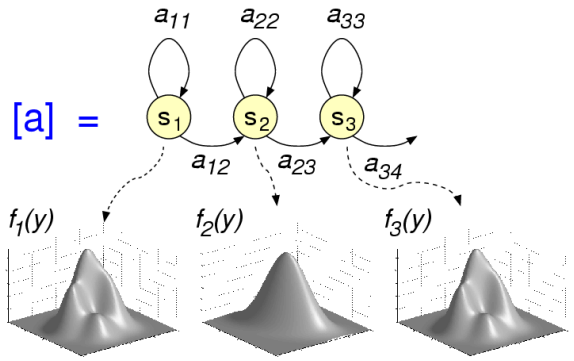
Hidden Markov Models



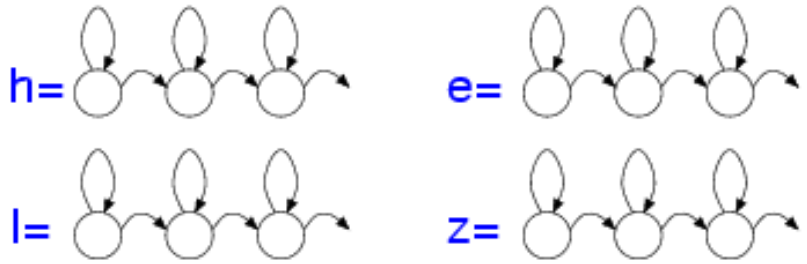

Transition Probabilities
HMM
Observation Probabilities
DNN
Frequency (kHz)
Time (s)
dBFS

[a]

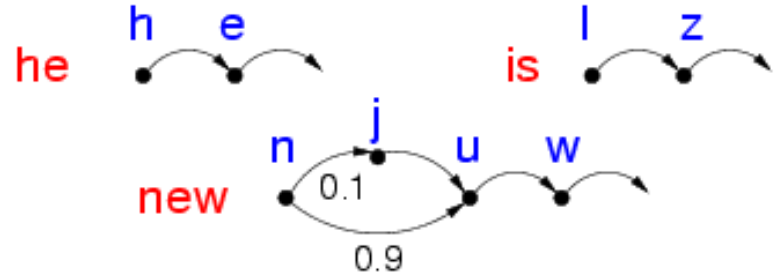
Hidden Markov Models



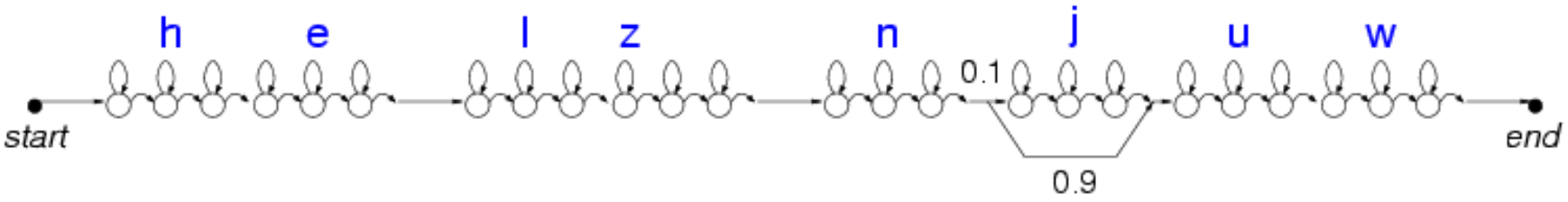
HMM phone models



Lexicon



Sentence model: 'he is new'



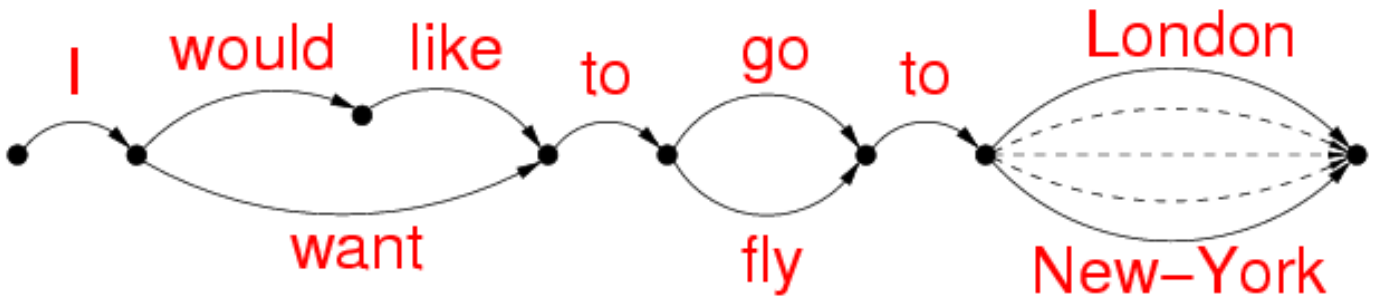
Grammar:

$$\langle \text{sentence}_1 \rangle = \text{I} \left\{ \begin{matrix} \text{would like} \\ \text{want} \end{matrix} \right\} \text{to} \left\{ \begin{matrix} \text{go} \\ \text{fly} \end{matrix} \right\} \text{to} \ \langle \text{airport} \rangle$$

$$\langle \text{sentence}_2 \rangle = \cdots$$

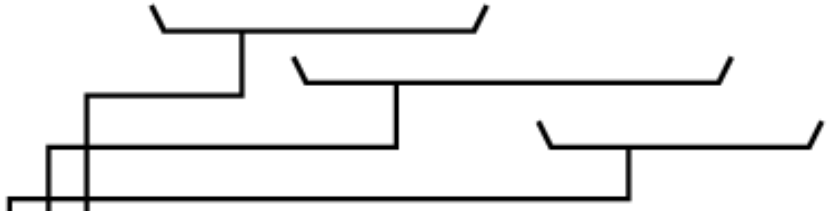
$$\langle \text{airport} \rangle = \{ \text{London}, \ \text{New–York}, \ldots \}$$

Finite–state representation:



N–gram language models

... the united states of ???

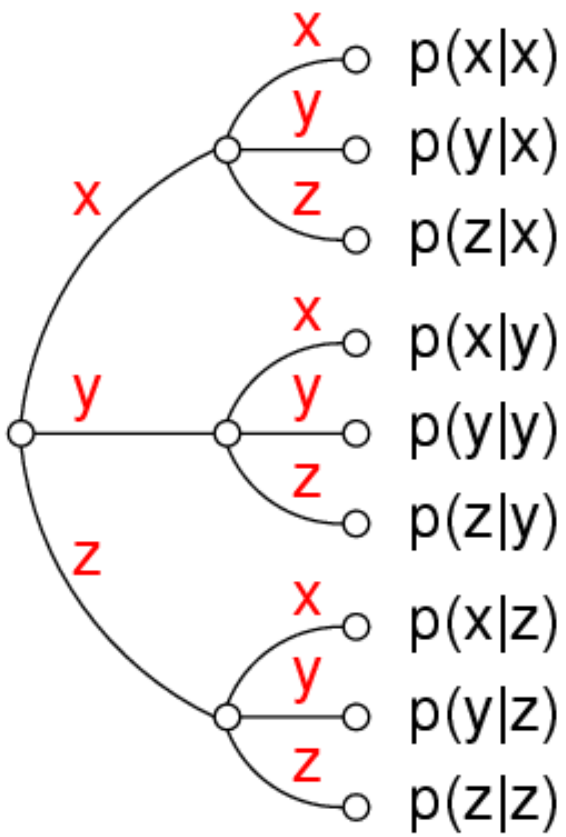


P(states | the united) = . . .

P(of | united states) = . . .

P(America | states of) = . . .

P(Belgium | states of) = . . .



Predict the next word, give a set of predecessor words

Language model

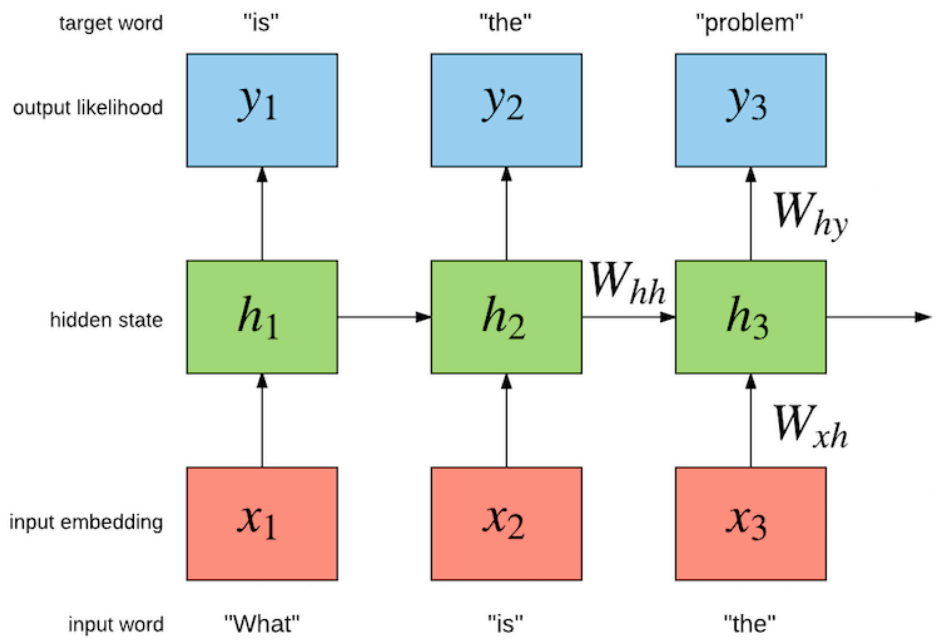
Language model is a probabilistic model used to

- Guide the search algorithm (predict next word given history)
- Disambiguate between phrases which are acoustically similar
  - Great wine vs Grey twine

It assigns probability to a sequence of tokens to be finally recognized

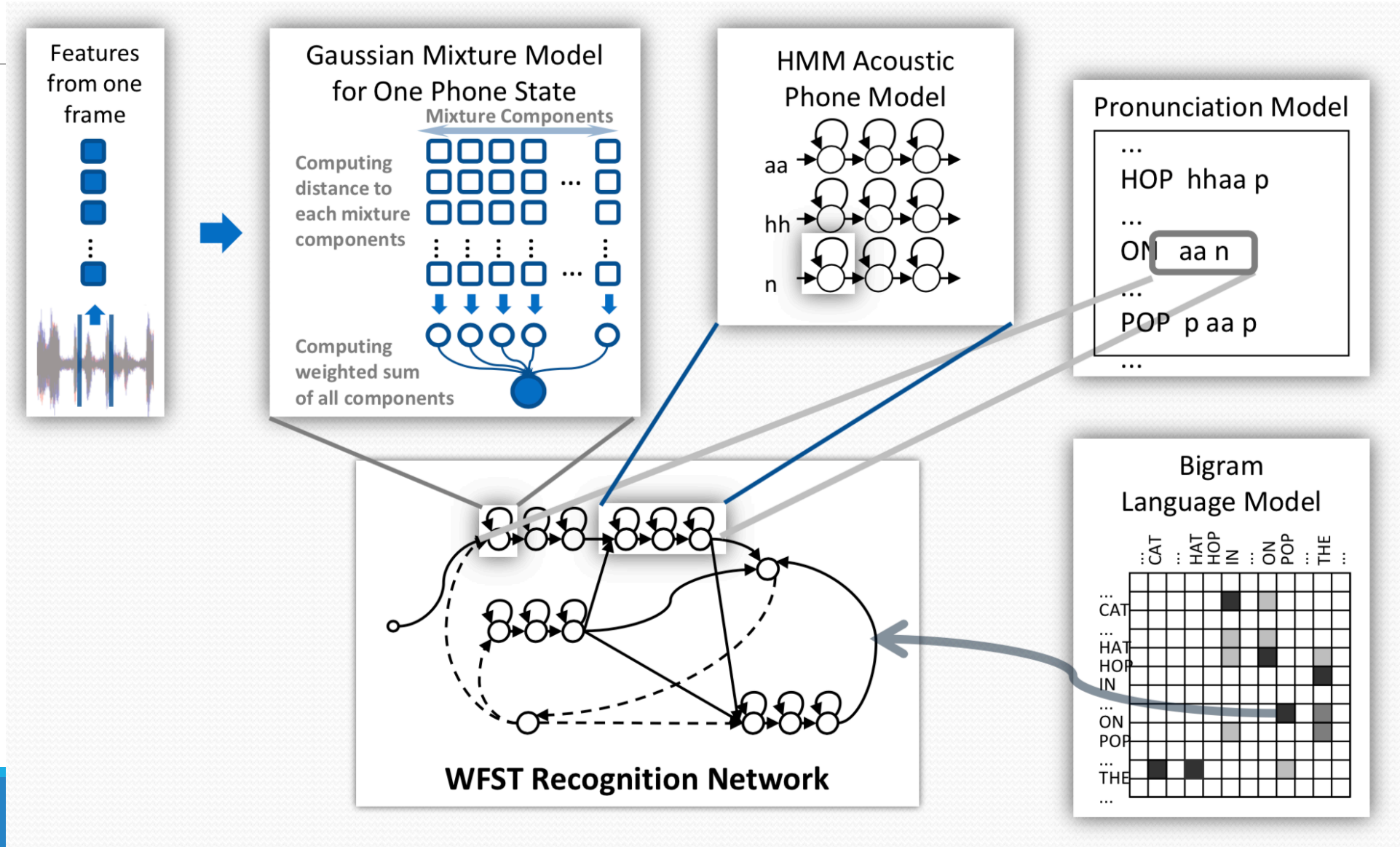
N-gram model $P(w_N|w_1, w_2, \cdots, w_{N-1})$

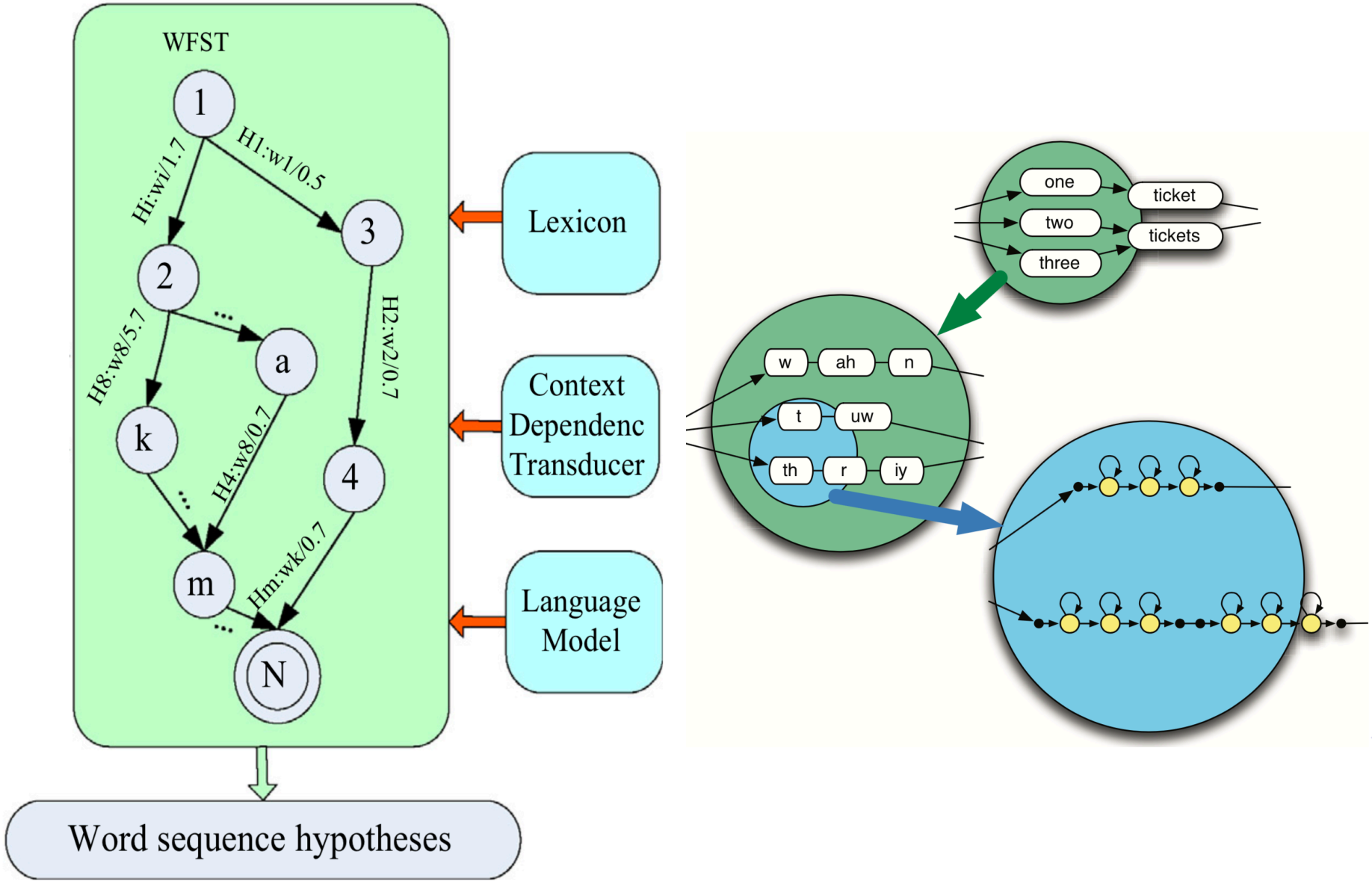
Recurrent neural network



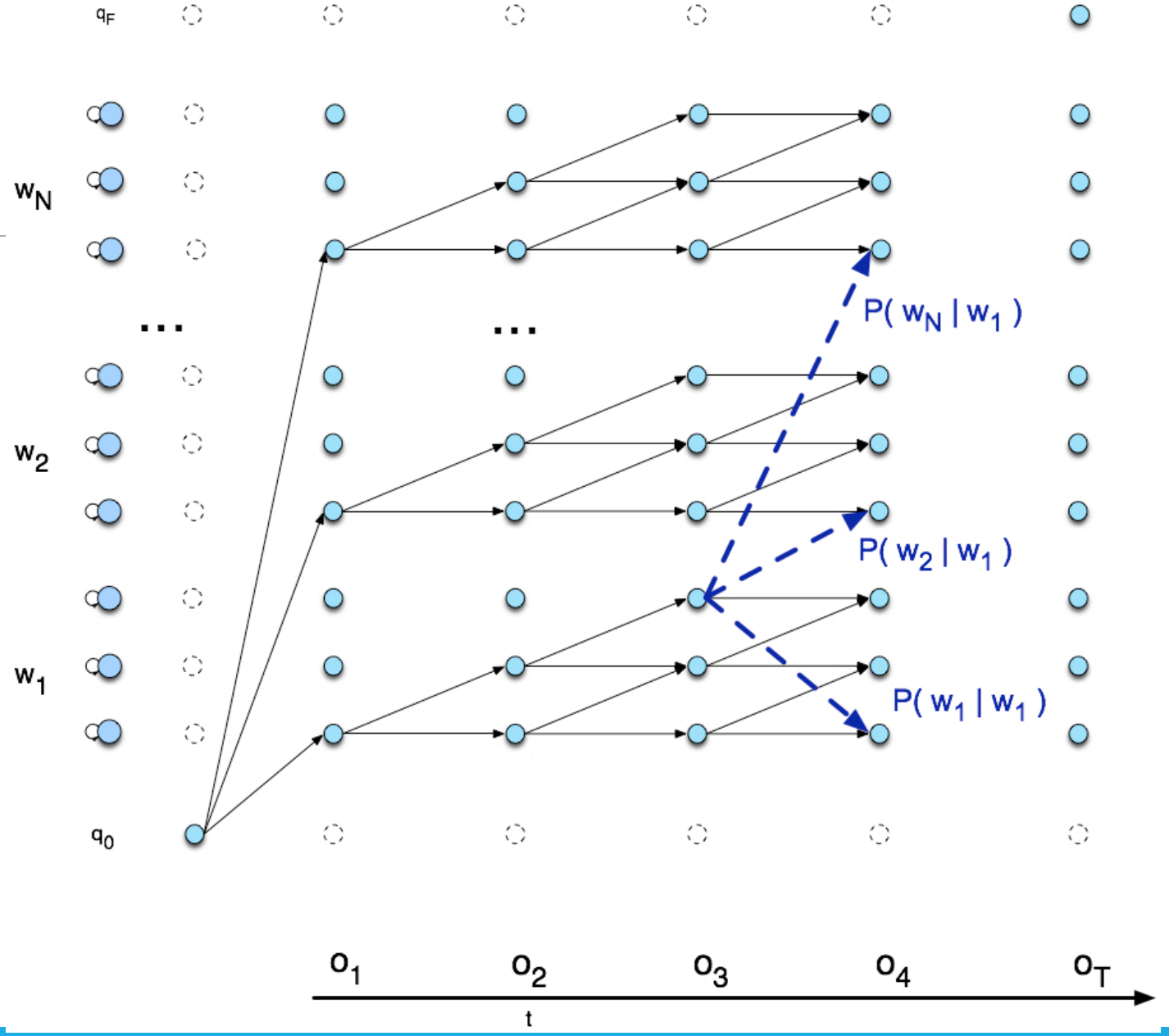
Recurrent neural network based Language model

Automatic Speech Recognizer

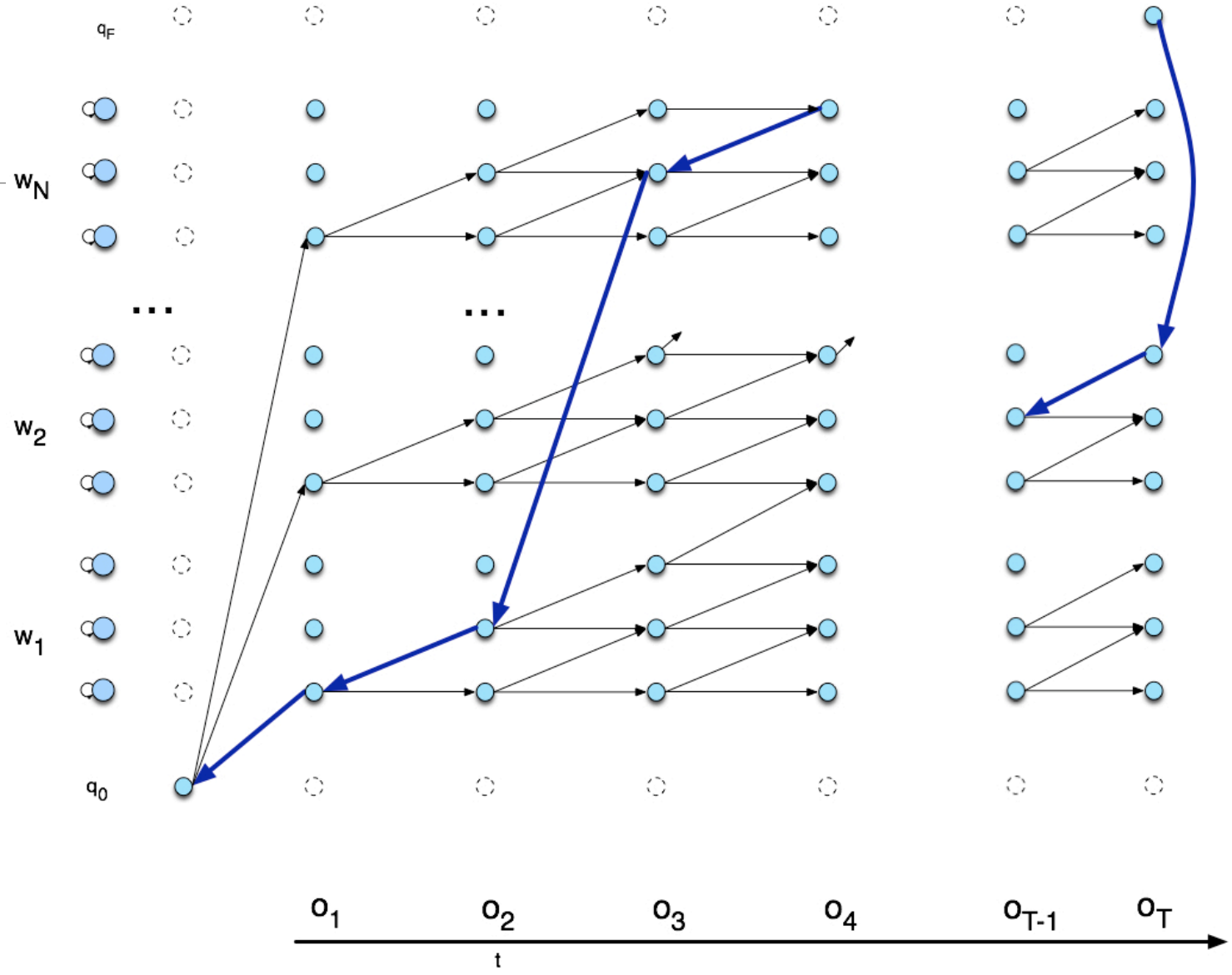



WFST
1
2
3
4
a
k
m
N
Hi:wi/1.7
H1:w1/0.5
H2:w2/0.7
H8:w8/5.7
H4:w8/0.7
Hm:wk/0.7
Lexicon
Context
Dependenc
Transducer
Language
Model
Word sequence hypotheses
one
two
three
ticket
tickets
w
ah
n
t
uw
th
r
iy

Viterbi Trellis

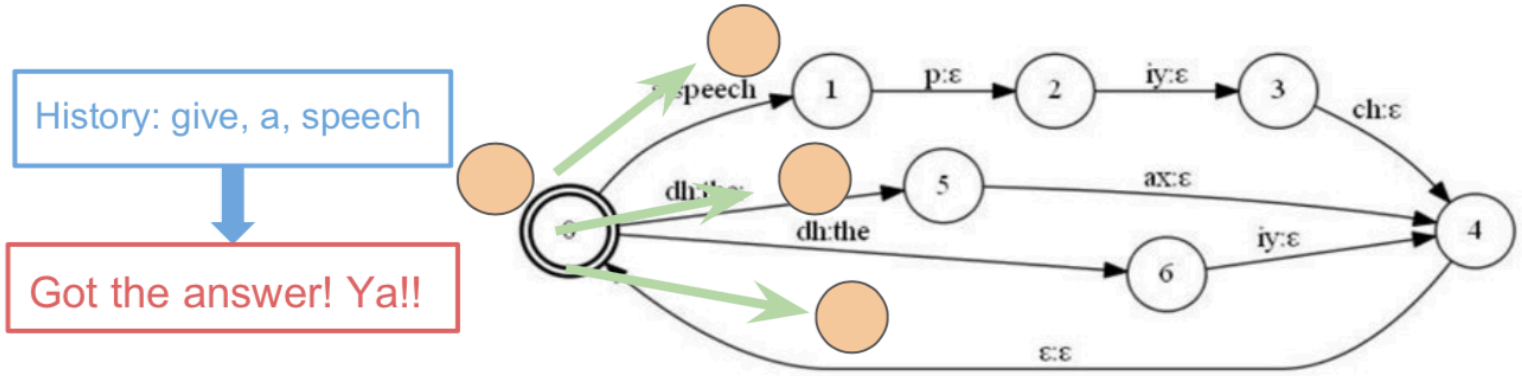


Viterbi Backtrace

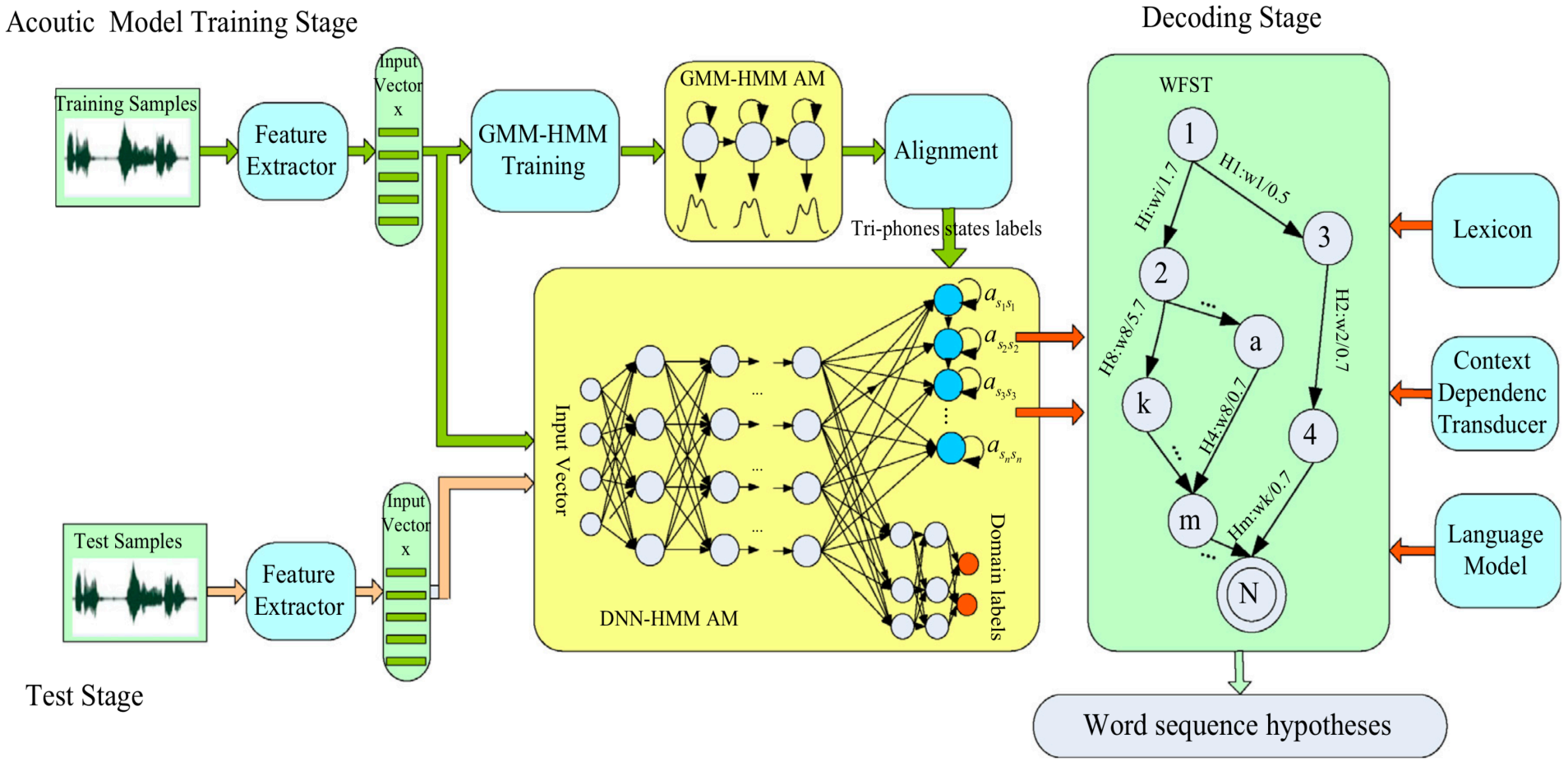


Token & Beam Pruning

- The loop of Decode:
  - Token Copy
  - Update AM/LM scores
  - Record the **`highest_score`** over all tokens
  - If **`Token.score < (highest_score - beam)`**, kill it. → beam pruning
- Finally, we choose the token with the highest score.
- Output it history words as answer.



Automatic Speech Recognizer

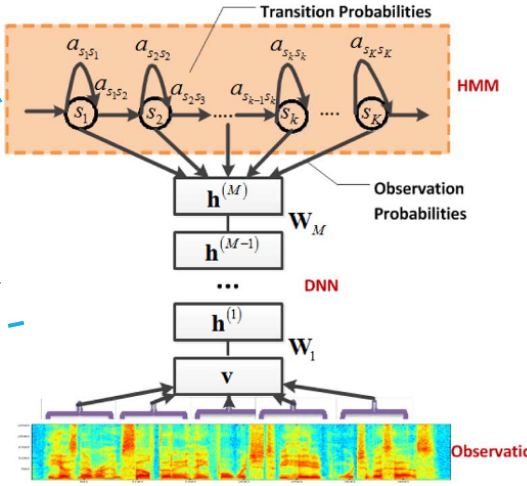


DNN-HMM

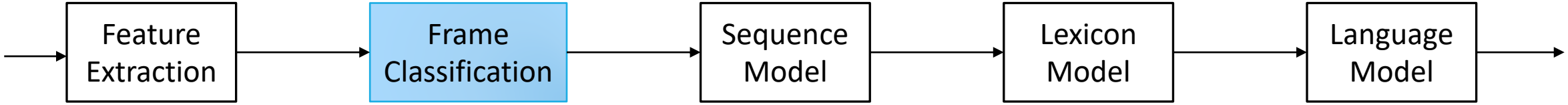
Kaldi

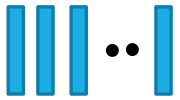
DNN: Deep Neural Networks

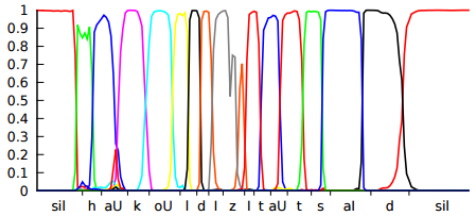
HMMs: Hidden Markov Models



DNNs HMMs







t ah m aa t ow

A Speech Audio

O Feature Frames

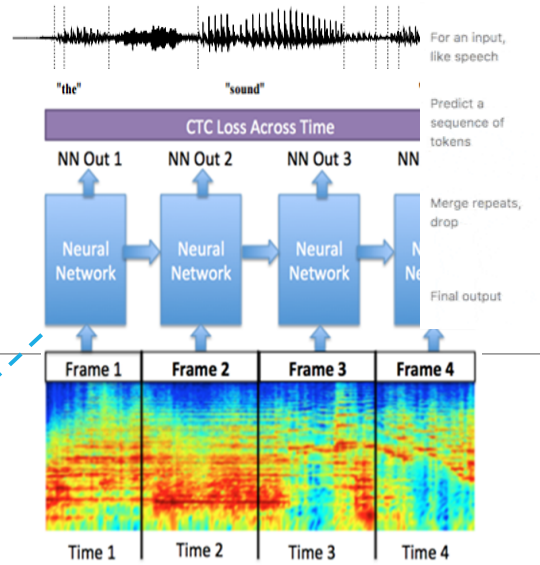
Q Sequence States

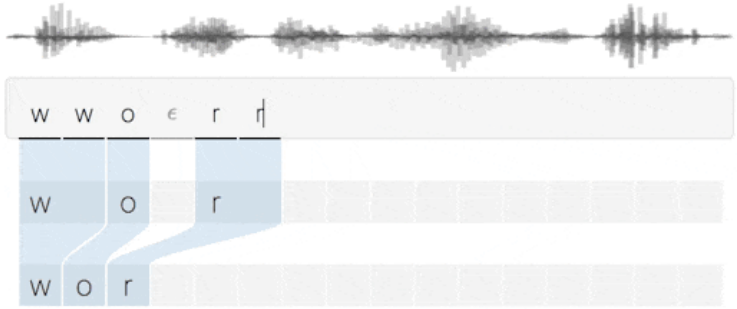
L Phonemes

W Words

Sentence

End-to-End: CTC



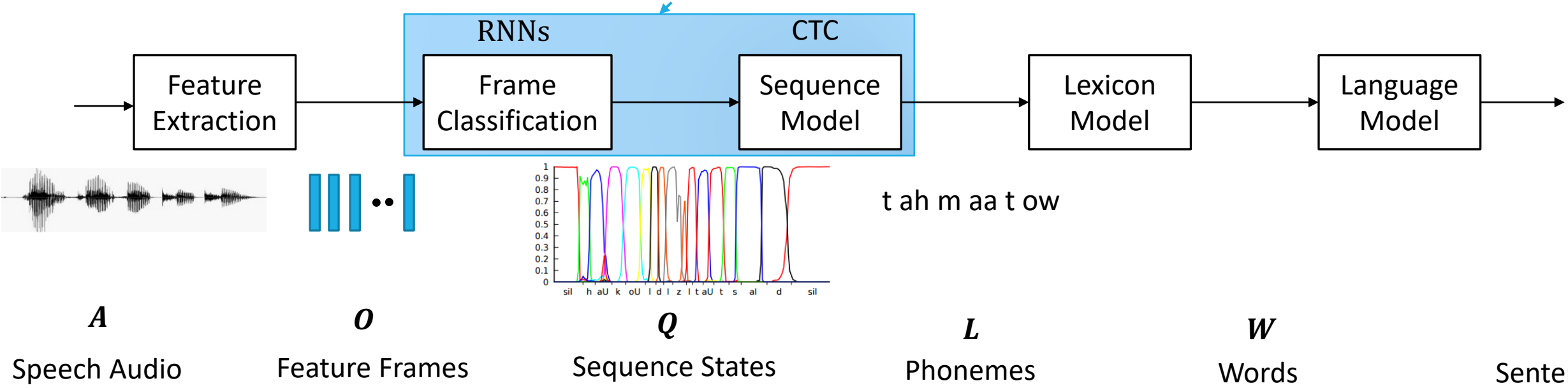


DeepSpeech2

RNN: Recurrent Neural Networks

CTC: Connectionist Temporal Classification

$$O^{ML}(S, \mathcal{N}_w) = -\sum_{(x,z)\in S} \ln\left(p(z|x)\right)$$



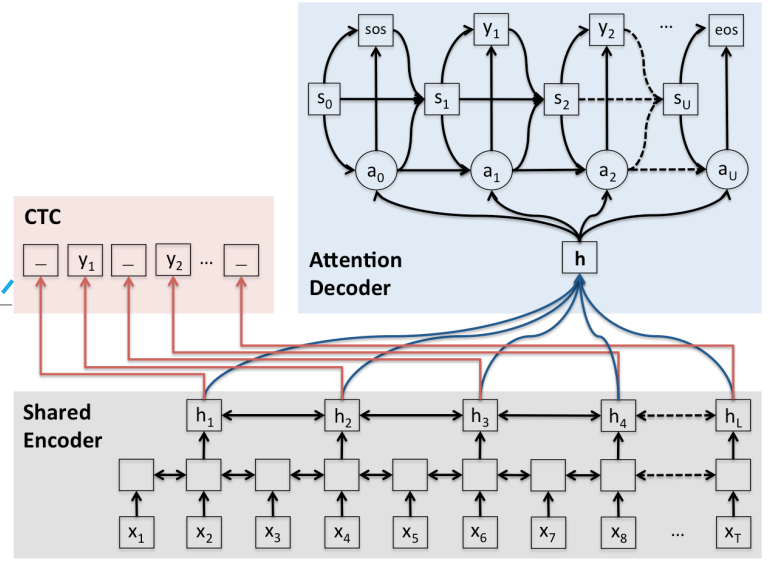
A	O	Q	L	W	
Speech Audio	Feature Frames	Sequence States	Phonemes	Words	Sentence

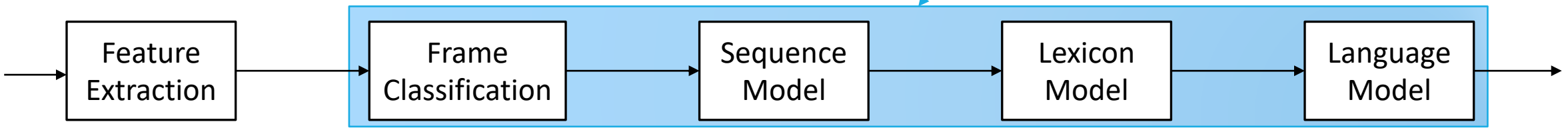
End-to-End: Attention

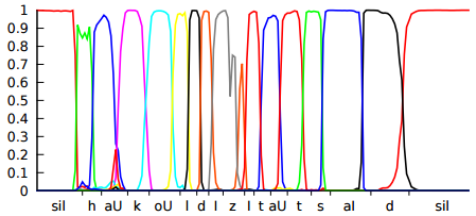
Listen, Attend and Spell

Predict character sequence directly

Sequence-to-Sequence with Attention







t ah m aa t ow

A Speech Audio

O Feature Frames

Q Sequence States

L Phonemes

W Words

Sentence