基于HMM的语音合成
HMM based Speech Synthesis

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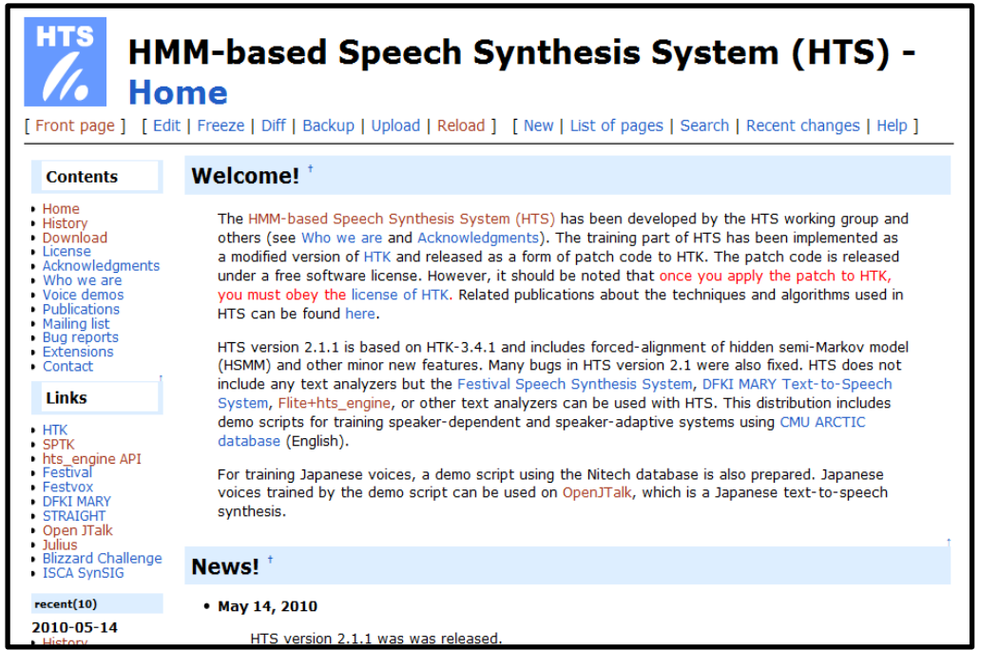
MEDIA JOINT Research Center

Adapted from HTS Slides

HTS Slides
released by HTS Working Group
http://hts.sp.nitech.ac.jp/

HTS: HMM-base Speech Synthesis System

- **HMM-based Speech Synthesis System (HTS)**
  - Released as a form of patch code to HTK
    - Under the New and Simplified BSD license
      - Once you apply the patch to HTK, you must obey the license of HTK
  - HTS-users mailing list
    - Over 500 posts per year
    - All posts are archived & searchable
    - Bug reports, Q&A, announce
  - Becoming a research platform
    - Using by various organizations (e. g., Microsoft, IBM)



http://hts.sp.nitech.ac.jp/

Outlines

- **Speech vocoding: Source-filter model**
- **Speech parameter modeling and generation with HMM**
  - Overview of HMM framework
  - State duration modeling
  - Spectrum modeling
  - F0 modeling
  - Context clustering
- **Voice character controlling**
  - Adaptation (mimicking voices)
  - Interpolation (mixing voices)
- **Application**
  - Singing voice
  - Emotional voice
  - Audio-visual speech synthesis

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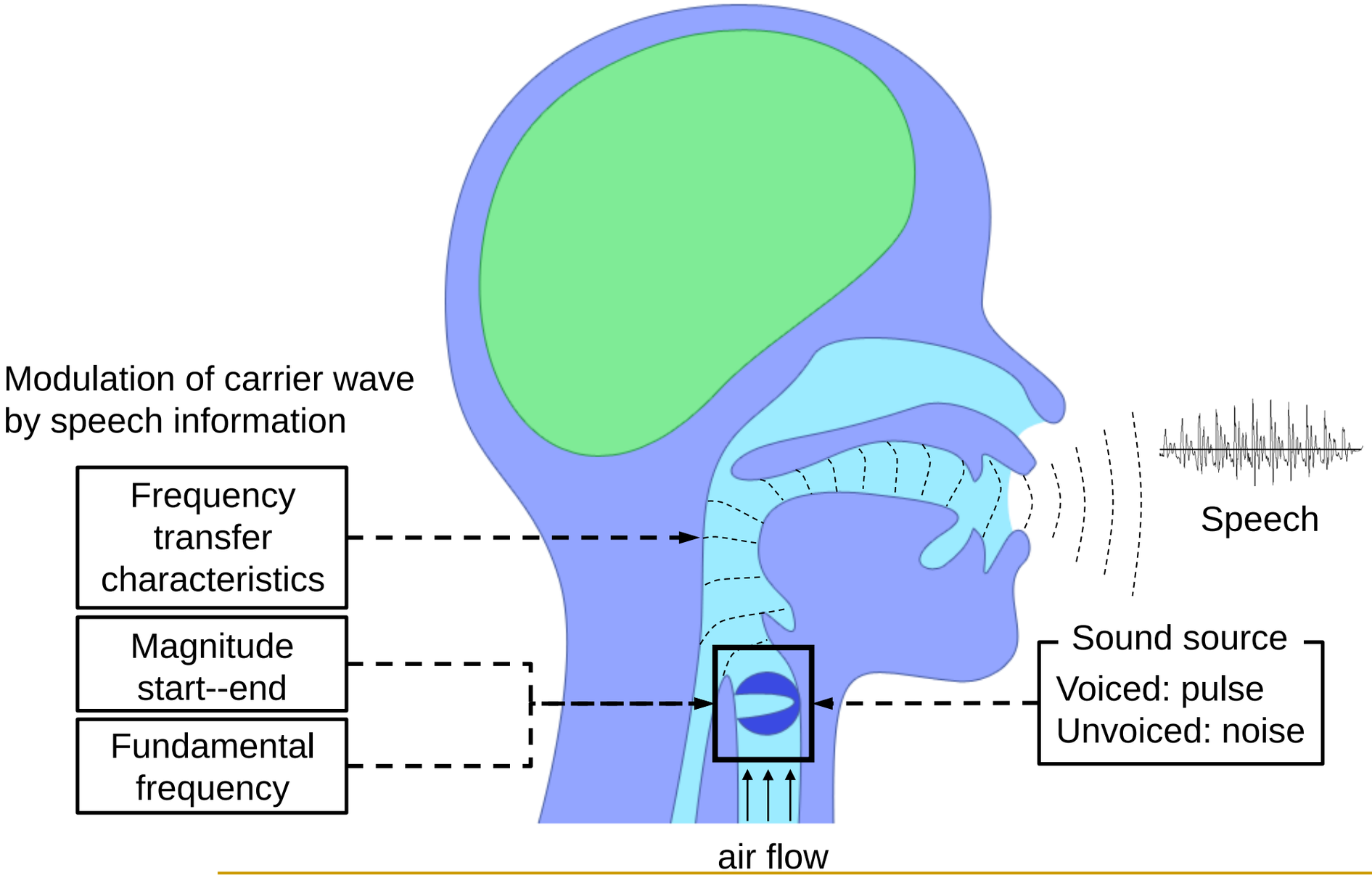
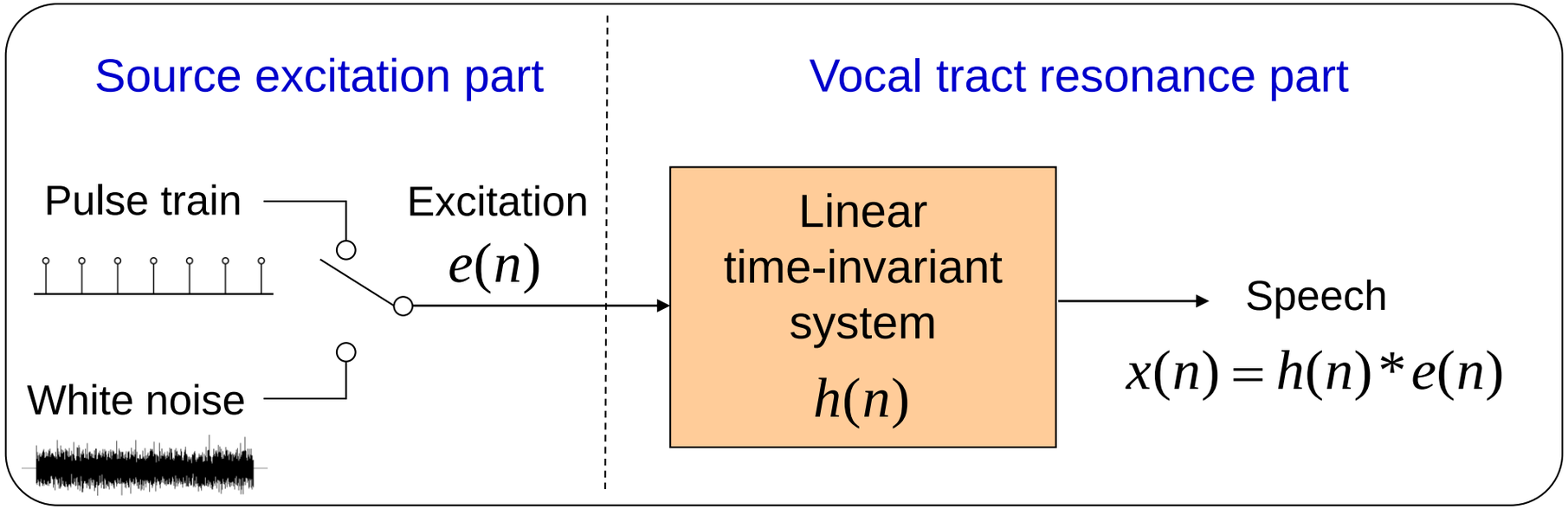
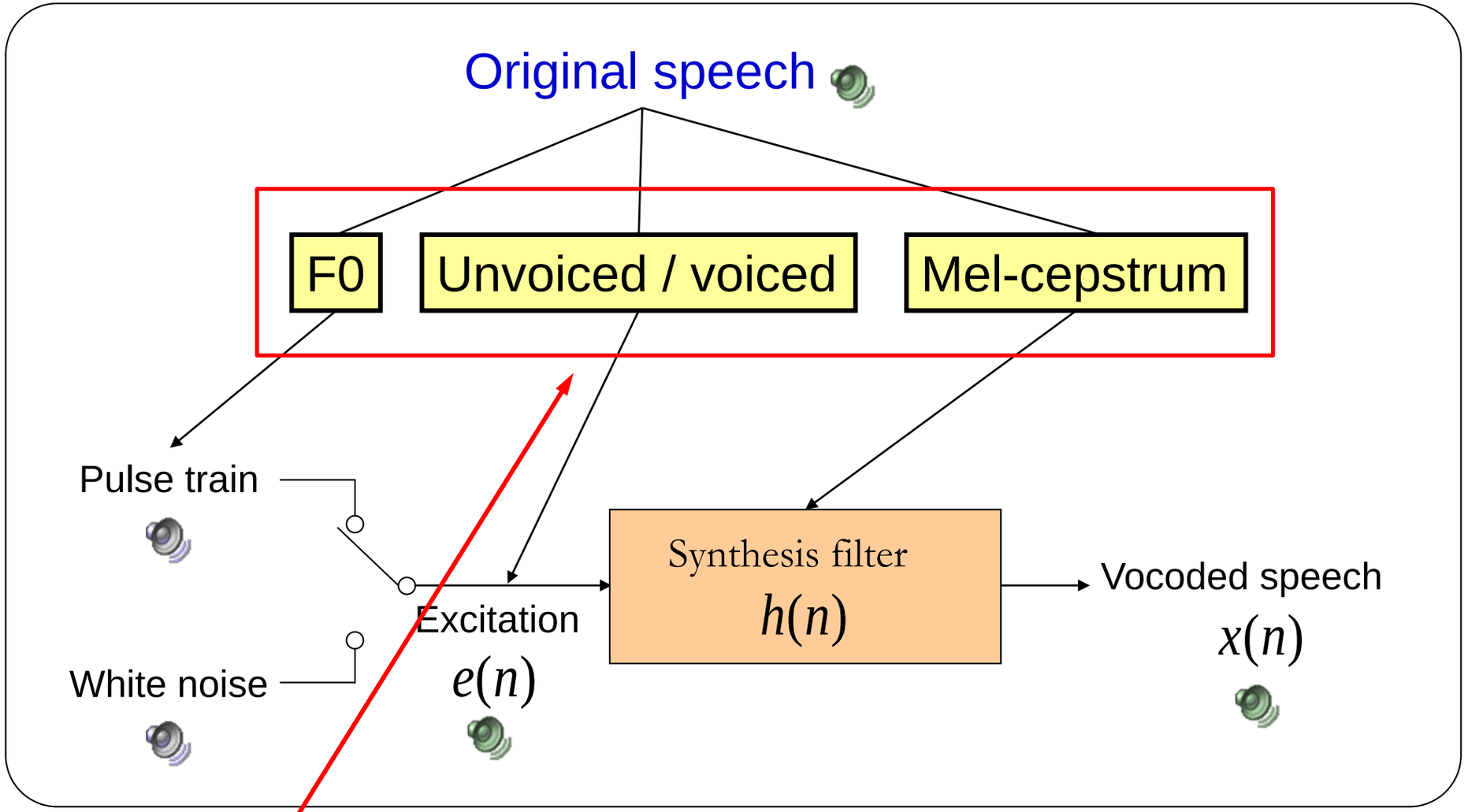
Speech Production Mechanism



Source-Filter Model

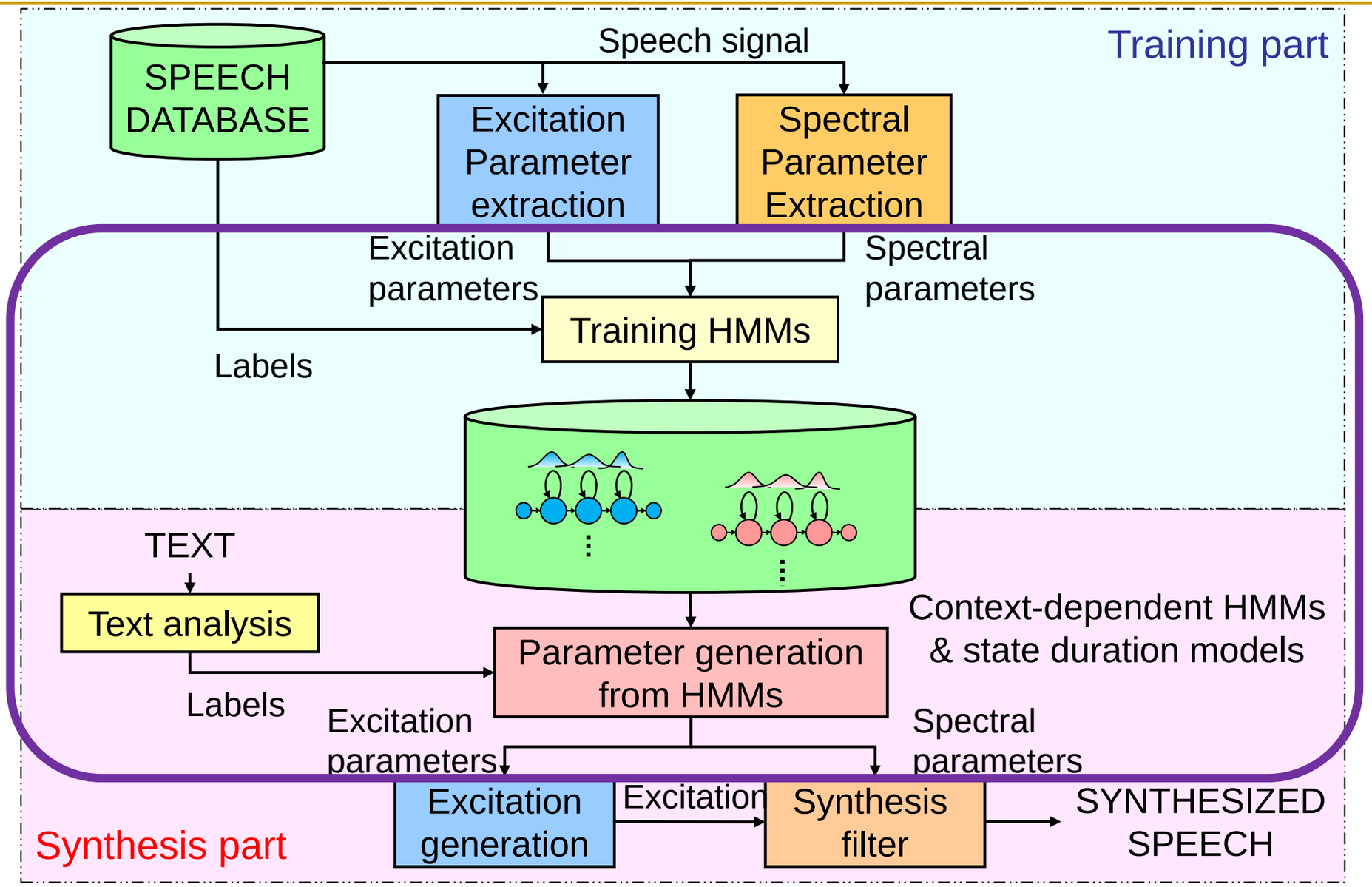


Overview of Speech Vocoding



These speech parameters are to be modeled by HMM

HMM-based Speech Synthesis System



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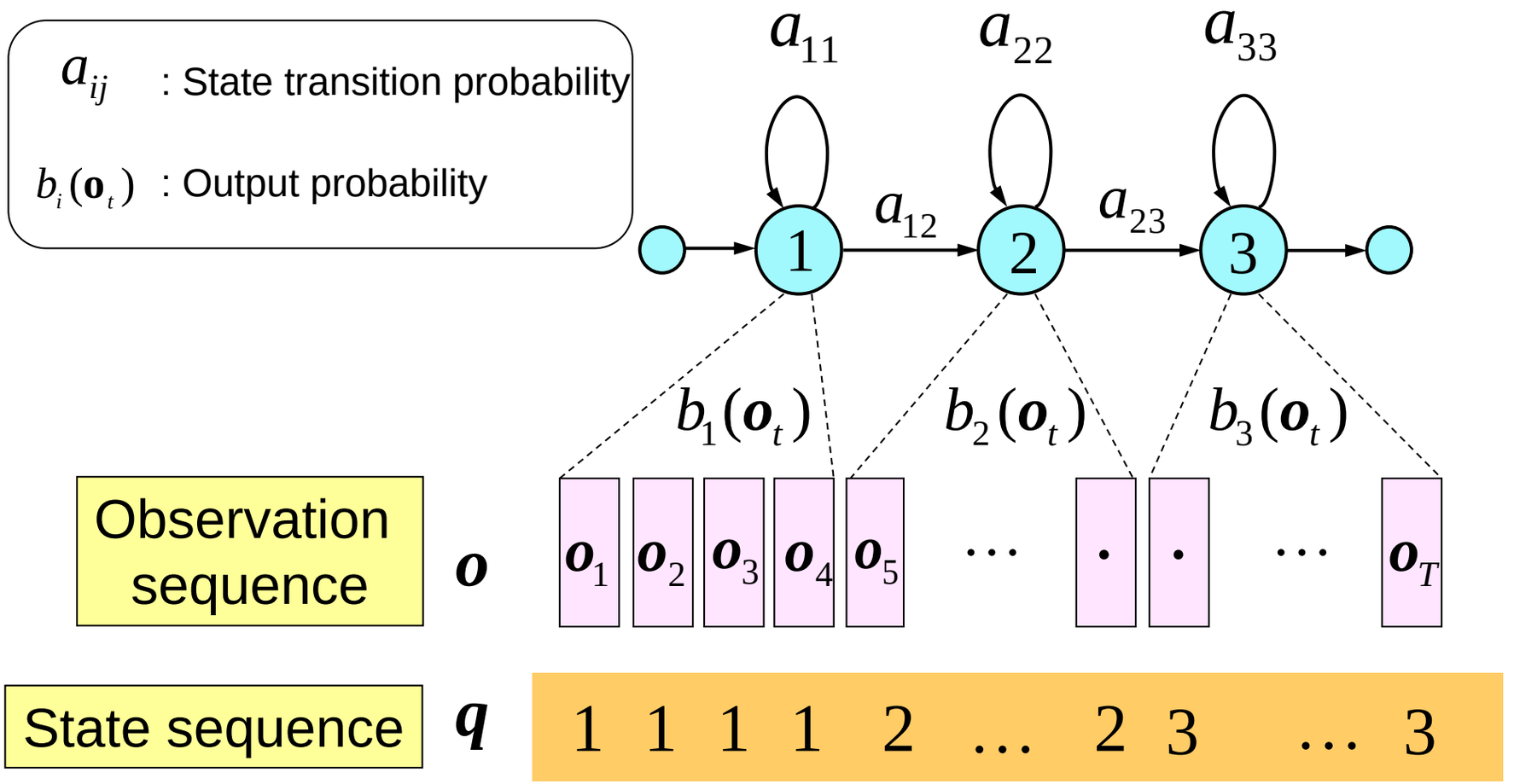
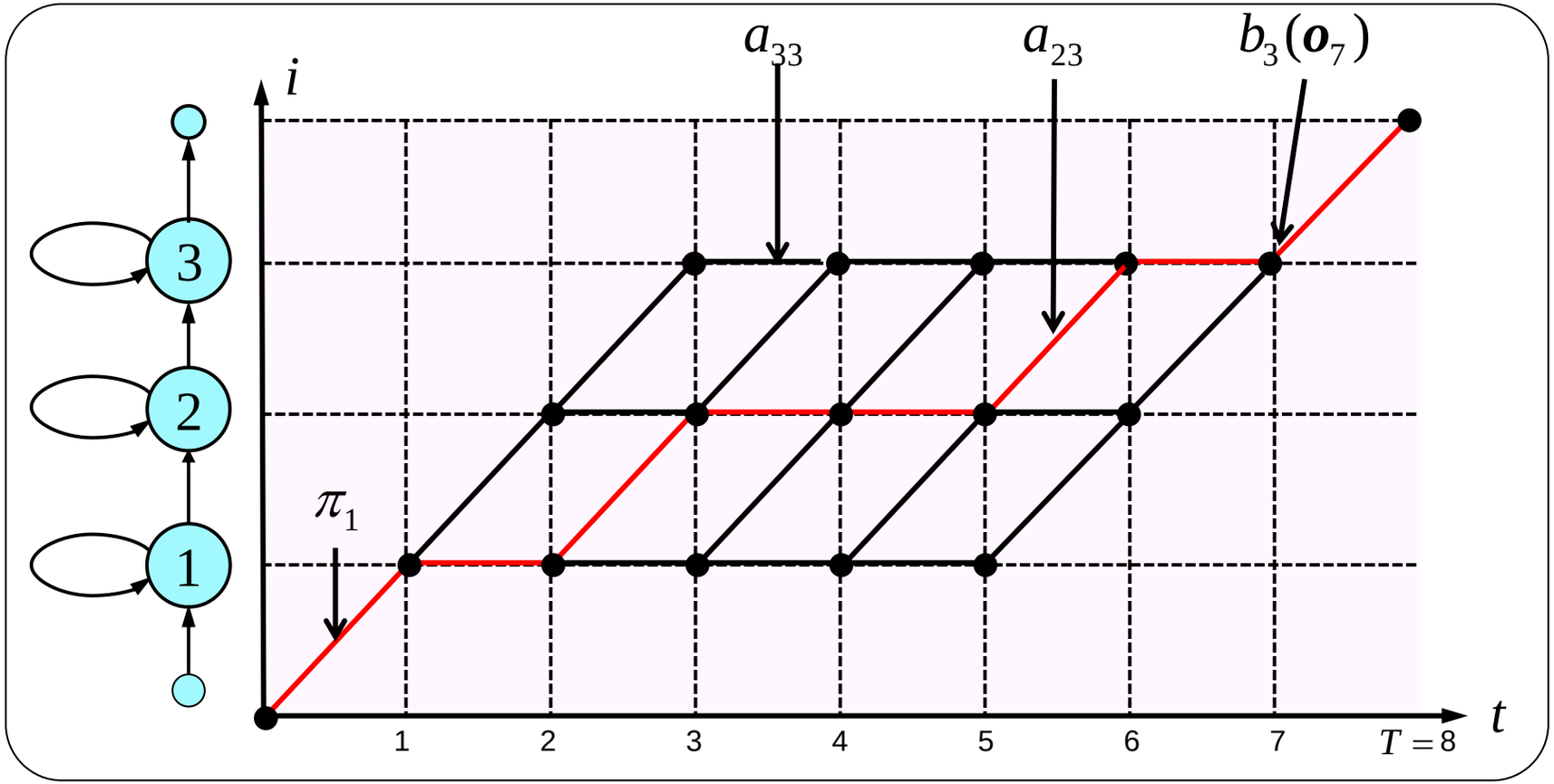
Hidden Markov Model (HMM)



The Markov chain whose state sequence is unknown
⇒ Estimating state sequence by the observation

Output Probability of HMM



Likelihood function

$$P(\boldsymbol{o}\mid\lambda)=\sum_{\boldsymbol{q}}P(\boldsymbol{o},\boldsymbol{q}\mid\lambda)=\sum_{\boldsymbol{q}}\prod_{t=1}^{T}a_{q_{t-1}q_t}b_{q_t}(\boldsymbol{o}_t)$$

Speech Parameter Generation Algorithm [Tokuda; '00]

For a given HMM $\boldsymbol{\lambda}$, determine a speech parameter vector sequence $\boldsymbol{o} = [\boldsymbol{o}_1^{\mathsf{T}}, \boldsymbol{o}_2^{\mathsf{T}}, \ldots, \boldsymbol{o}_T^{\mathsf{T}}]^{\mathsf{T}}$ which maximizes

$$\hat{\mathbf{o}} = \arg\max_{\mathbf{o}} P(\mathbf{o} \mid \boldsymbol{\lambda}) = \arg\max_{\mathbf{o}} \sum_{\mathbf{q}} P(\mathbf{o} \mid \mathbf{q}, \boldsymbol{\lambda}) P(\mathbf{q} \mid \boldsymbol{\lambda})$$

$$\approx \arg\max_{\mathbf{q},\mathbf{o}} P(\mathbf{o} \mid \mathbf{q}, \boldsymbol{\lambda}) P(\mathbf{q} \mid \boldsymbol{\lambda})$$

$$\Downarrow$$

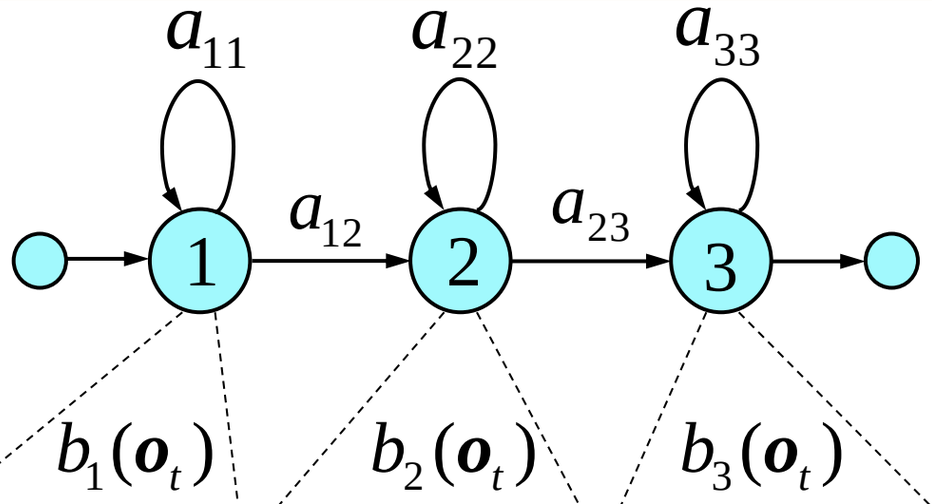
$$\hat{\boldsymbol{q}} = \arg\max_{\boldsymbol{q}} P(\boldsymbol{q} \mid w, \boldsymbol{\lambda})$$

$$\hat{\boldsymbol{o}} = \arg\max_{\boldsymbol{o}} P(\boldsymbol{o} \mid \hat{\boldsymbol{q}}, \boldsymbol{\lambda})$$

Determination of State Sequence

a_{ij} : State transition probability

$b_i(\mathbf{o}_t)$: Output probability



Observation sequence

$\boldsymbol{o}$ $\boldsymbol{o}_1$ $\boldsymbol{o}_2$ $\boldsymbol{o}_3$ $\boldsymbol{o}_4$ $\boldsymbol{o}_5$ … . . … $\boldsymbol{o}_T$

State sequence

$\boldsymbol{q}$ 1 1 1 1 2 … 2 3 … 3

$$\hat{\mathbf{q}} = \arg\max_{\mathbf{q}} P(\mathbf{q} \mid w, \boldsymbol{\lambda})$$

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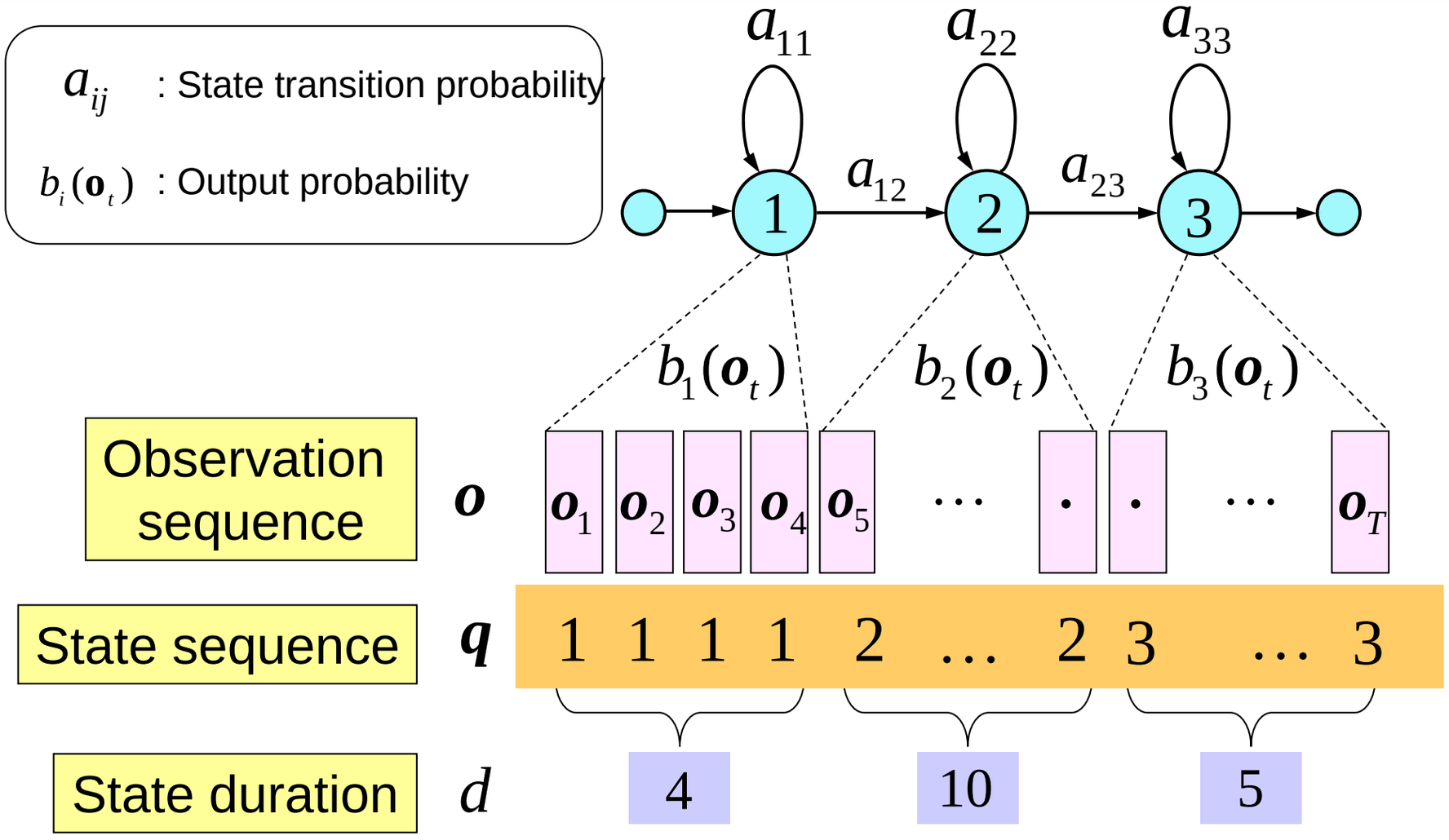
Determination of State Sequence



Determine state sequence via determining state durations

Determination of State Sequence

$$\hat{\mathbf{q}} = \arg\max_{\mathbf{q}} P(\mathbf{q} \mid w, \boldsymbol{\lambda})$$

$$P(\mathbf{q} \mid w, \boldsymbol{\lambda}) = \prod_{i=1}^{K} p_i(d_i)$$

$p_i(\cdot)$: state-duration distribution of i-th state

d_i : state duration of i-th state

K : # of states in a sentence HMM for w

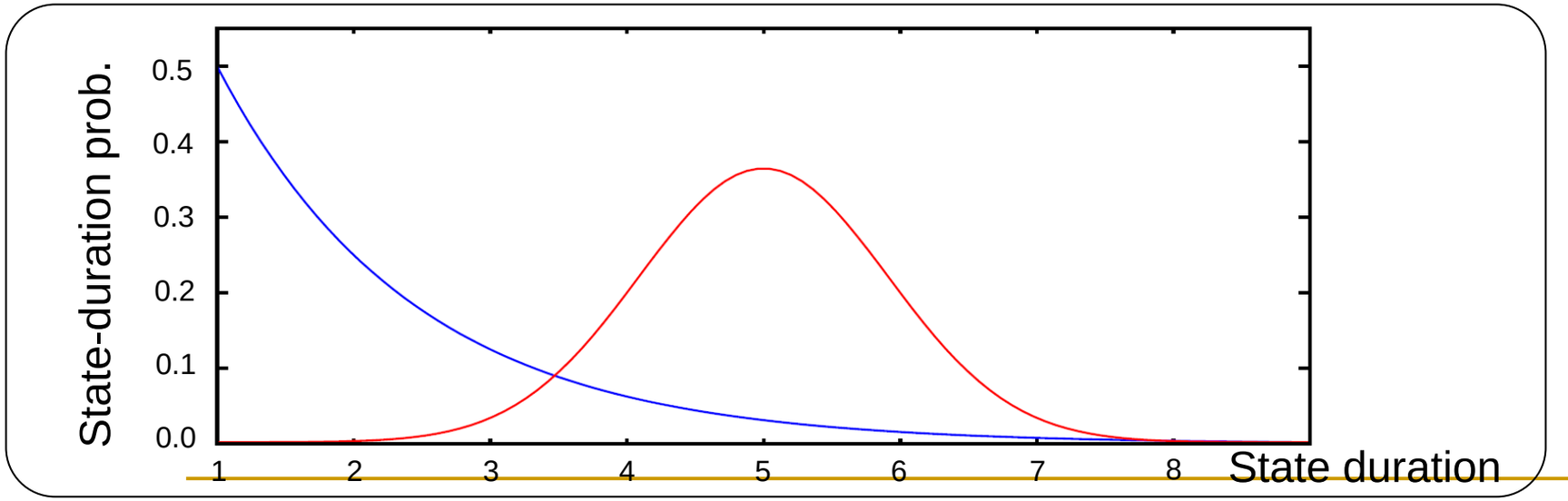
State Duration Modeling

Geometric

$$p_i(d_i) = a_{ii}^{d_i - 1}(1 - a_{ii}) \quad \Rightarrow \quad \hat{d}_i = 1$$

Gaussian

$$p_i(d_i) = N(d_i \mid m_i, \sigma_i^2) \quad \Rightarrow \quad \hat{d}_i = m_i$$



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$$\approx \max_{\boldsymbol{q}} P(\boldsymbol{o} \mid \boldsymbol{q}, \boldsymbol{\lambda}) P(\boldsymbol{q} \mid \boldsymbol{\lambda})$$

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$$\hat{\boldsymbol{q}} = \arg\max_{\boldsymbol{q}} P(\boldsymbol{q} \mid w, \boldsymbol{\lambda})$$

$$\hat{\boldsymbol{o}} = \arg\max_{\boldsymbol{o}} P(\boldsymbol{o} \mid \hat{\boldsymbol{q}}, \boldsymbol{\lambda})$$

Determination of State Output

$$\hat{\mathbf{o}} = \arg\max_{\mathbf{o}} P(\mathbf{o} \mid \hat{\mathbf{q}}, \boldsymbol{\lambda})$$

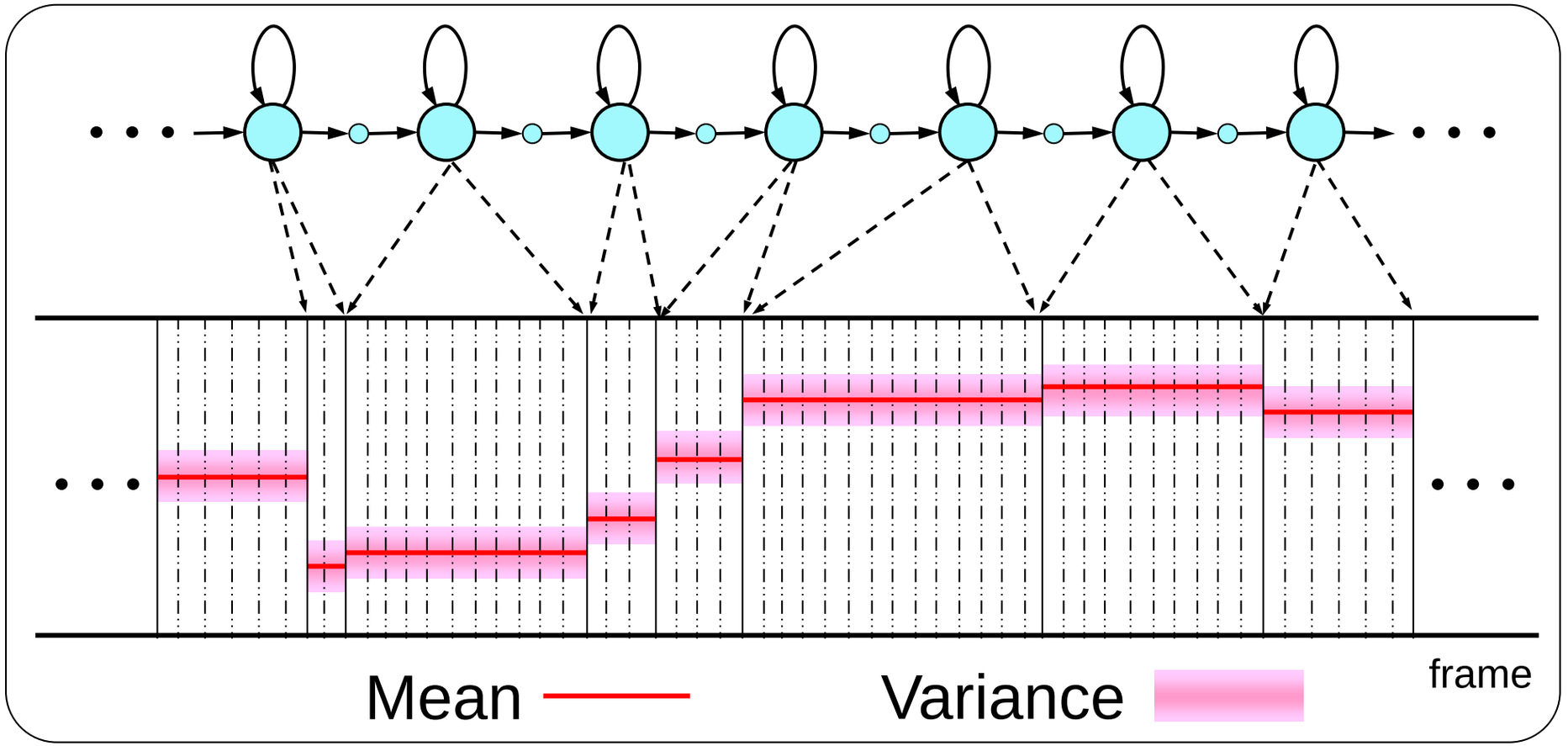
$$P(\mathbf{o} \mid \hat{\mathbf{q}}, \boldsymbol{\lambda}) = \prod_{t=1}^{T} b_{q_t}(\mathbf{o}_t)$$

Gaussian distribution

$$b_j(\mathbf{o}_t) = N(\mathbf{o}_t \mid \boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j)$$

$$\hat{\mathbf{o}}_t = \boldsymbol{\mu}_j$$

Generated Feature Sequence



$\hat{o}$ becomes a sequence of mean vectors

⇒ discontinuous outputs between states

To Solve the Problem …

Constrained with dynamic features!

Let the speech parameter vector $\mathbf{o}_t$ at frame t consists of the static feature vector $\mathbf{c}_t$ and the dynamic feature vector $\Delta\mathbf{c}_t$:

$$\mathbf{o}_t = \{\mathbf{c}_t, \Delta\mathbf{c}_t\}$$

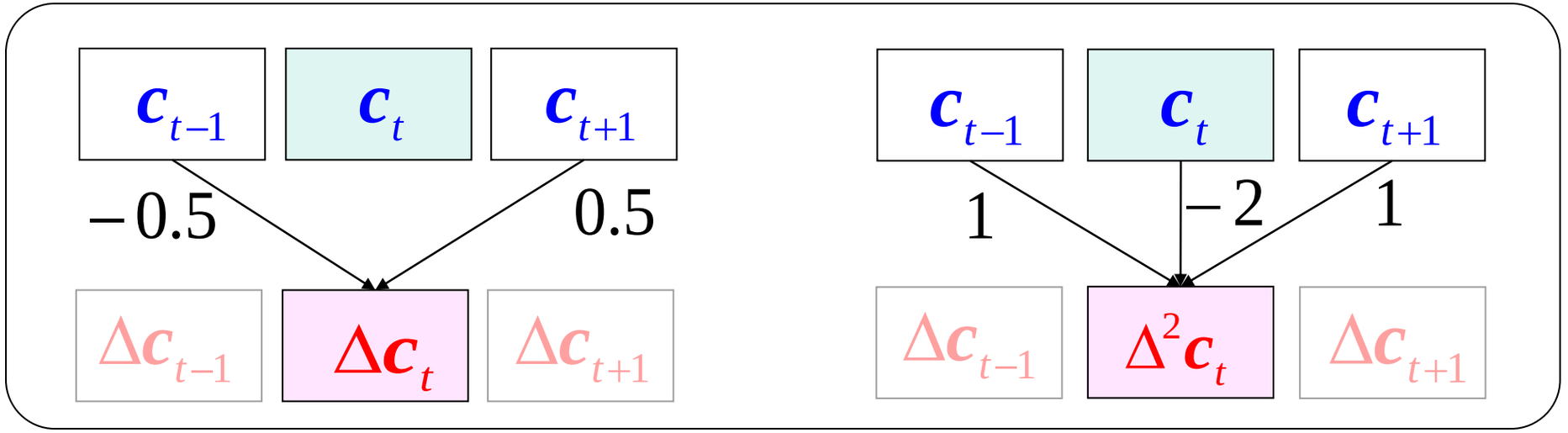
Assume $\mathbf{c}_t$ and $\Delta\mathbf{c}_t$ are statistically independent, then

$$P(\mathbf{o} \mid \hat{\mathbf{q}}, \boldsymbol{\lambda}) = \prod_{t=1}^{T} b_{q_t}(\mathbf{o}_t) = \prod_{t=1}^{T} b_{q_t}(\mathbf{c}_t) b_{q_t}(\Delta\mathbf{c}_t)$$

Dynamic Features

$$\Delta \boldsymbol{c}_t = \frac{\partial \boldsymbol{c}_t}{\partial t} \approx 0.5(\boldsymbol{c}_{t+1} - \boldsymbol{c}_{t-1})$$

$$\Delta^2 \boldsymbol{c}_t = \frac{\partial^2 \boldsymbol{c}_t}{\partial t^2} \approx \boldsymbol{c}_{t+1} - 2\boldsymbol{c}_t + \boldsymbol{c}_{t-1}$$



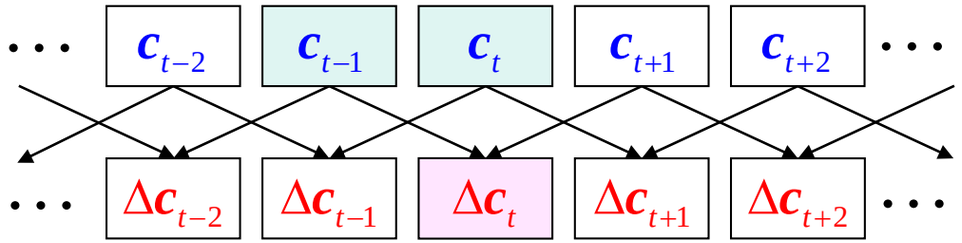
Integration of Dynamic Features

Speech parameter vector $\boldsymbol{o}_t$ includes both static & dynamic features

$$\boldsymbol{o}_t = \left[\boldsymbol{c}_t^{\mathsf{T}}, \Delta\boldsymbol{c}_t^{\mathsf{T}} \right]^{\mathsf{T}}$$

$2M$ = M + M

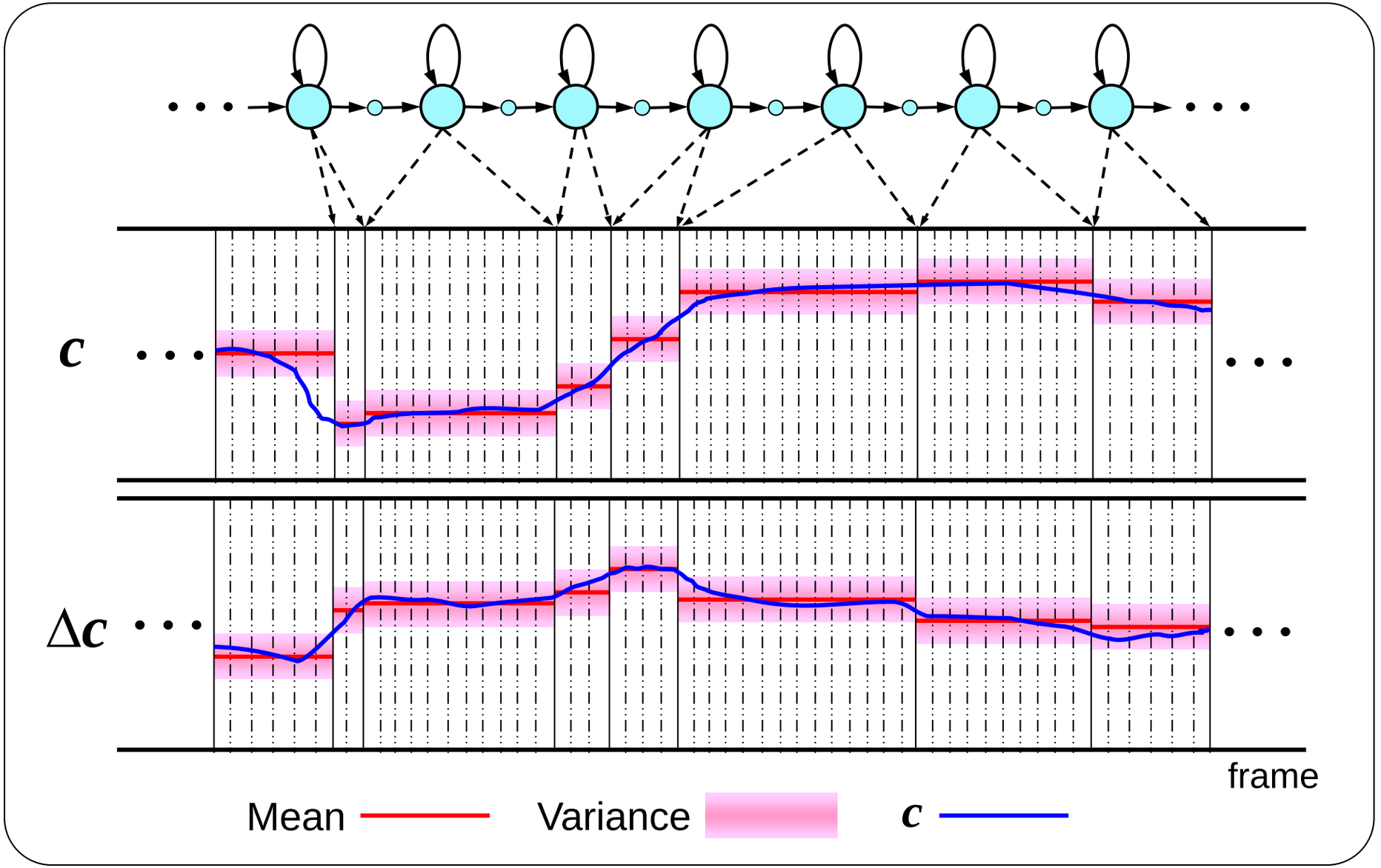
$$\Delta\boldsymbol{c}_t = 0.5(\boldsymbol{c}_{t+1} - \boldsymbol{c}_{t-1})$$



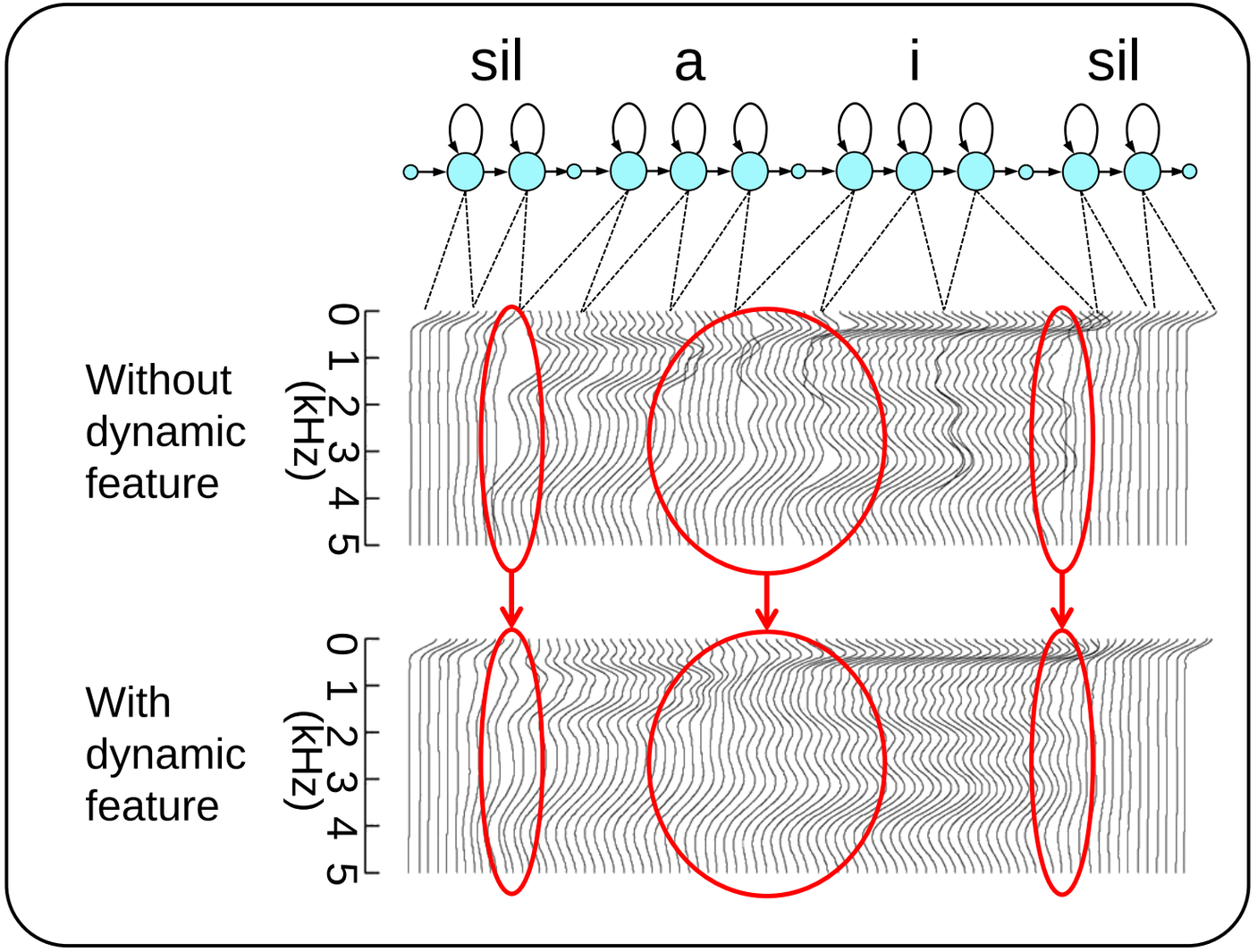
The relationship between $\boldsymbol{o}_t$ & $\boldsymbol{c}_t$ can be arranged as

$$\begin{bmatrix} \vdots \\ \boldsymbol{c}_{t-1} \\ \Delta\boldsymbol{c}_{t-1} \\ \boldsymbol{c}_t \\ \Delta\boldsymbol{c}_t \\ \boldsymbol{c}_{t+1} \\ \Delta\boldsymbol{c}_{t+1} \\ \vdots \end{bmatrix} \begin{matrix} \\ \boldsymbol{o}_{t-1} \\ \\ \boldsymbol{o}_t \\ \\ \boldsymbol{o}_{t+1} \\ \\ \end{matrix} = \begin{bmatrix} \cdots & \vdots & \vdots & \vdots & \vdots & \cdots \\ \cdots & \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{0} & \boldsymbol{0} & \cdots \\ \cdots & -1/2\,\boldsymbol{I} & \boldsymbol{0} & 1/2\,\boldsymbol{I} & \boldsymbol{0} & \cdots \\ \cdots & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{0} & \cdots \\ \cdots & \boldsymbol{0} & -1/2\,\boldsymbol{I} & \boldsymbol{0} & 1/2\,\boldsymbol{I} & \cdots \\ \cdots & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{I} & \cdots \\ \cdots & \boldsymbol{0} & \boldsymbol{0} & -1/2\,\boldsymbol{I} & \boldsymbol{0} & \cdots \\ \cdots & \vdots & \vdots & \vdots & \vdots & \cdots \end{bmatrix} \begin{matrix} \\ \\ \boldsymbol{c}_{t-2} \\ \boldsymbol{c}_{t-1} \\ \boldsymbol{c}_t \\ \boldsymbol{c}_{t+1} \\ \\ \end{matrix} \begin{matrix} \boldsymbol{o} \\ \\ \\ \\ \\ \\ \\ \\ \end{matrix} \quad \boldsymbol{W}\ (M \times N) \quad \boldsymbol{c} \quad N$$

Generated Speech Parameter Trajectory



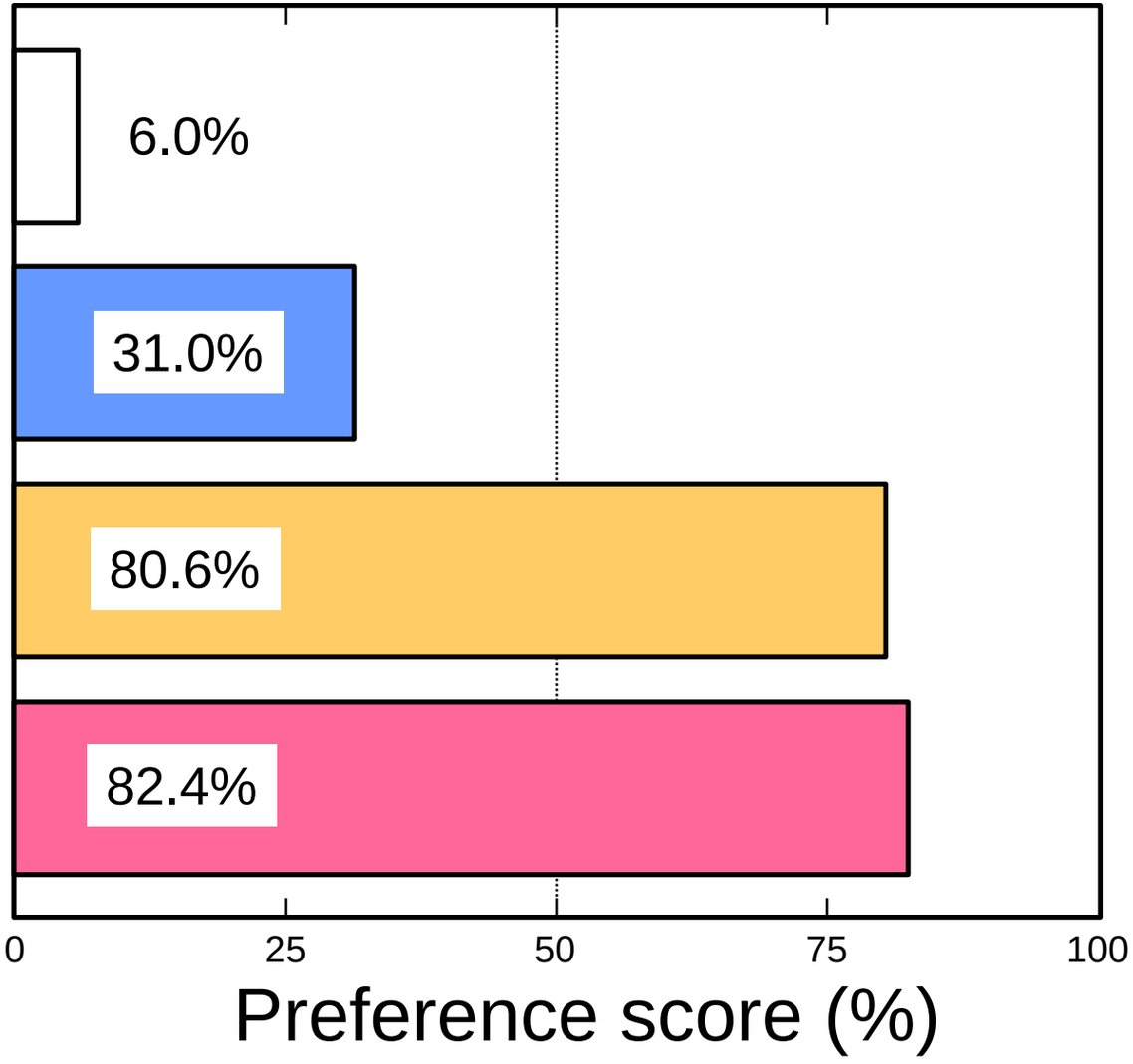
Generated Spectra



Spectra changing smoothly between phonemes

Effect of Dynamic Features (Japanese)

- static
- liner interpolation
- static + Δ
- static + $\Delta + \Delta^2$



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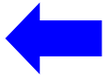
  - F0 modeling 
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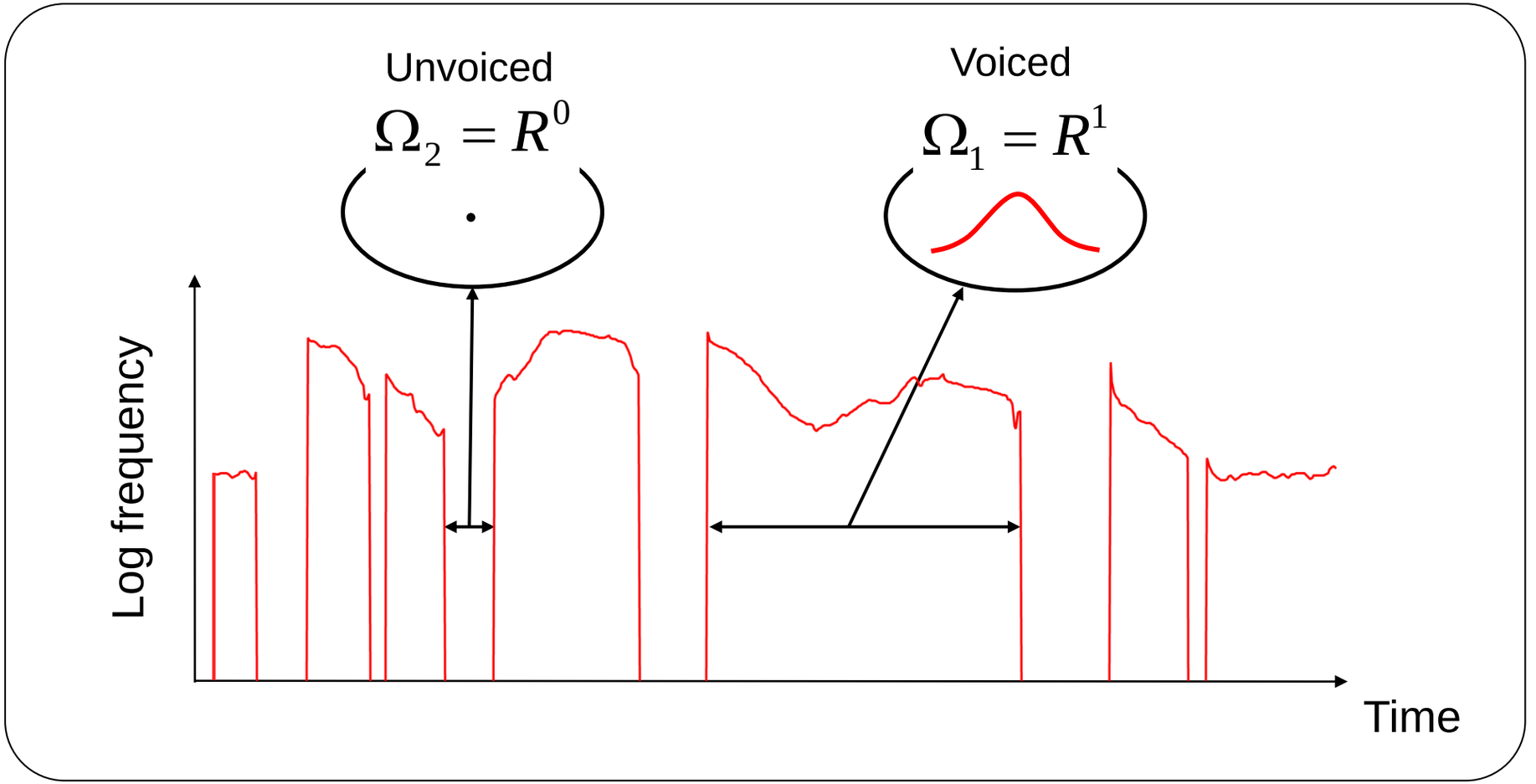
Observation of F0

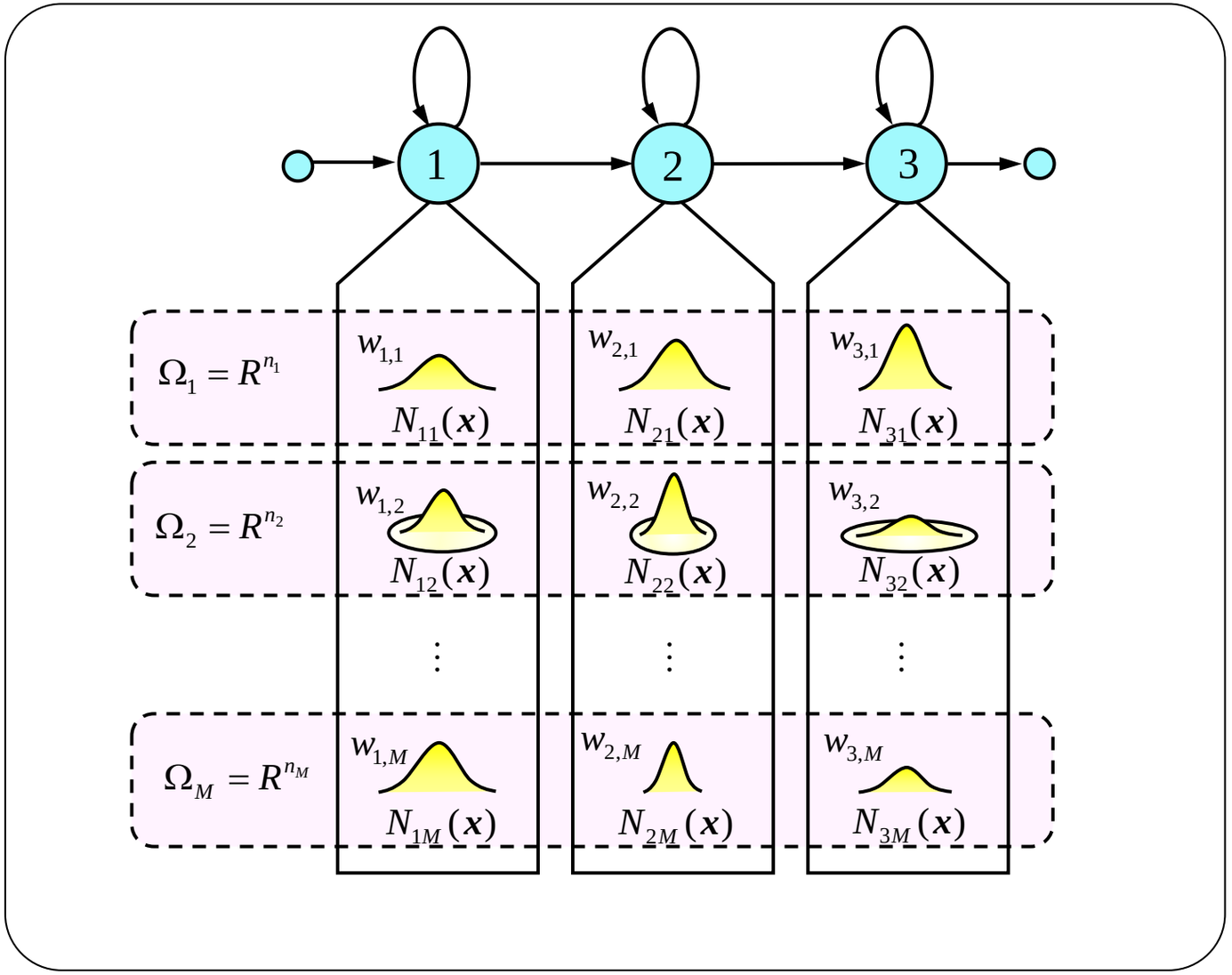


Unable to model by continuous or discrete distribution

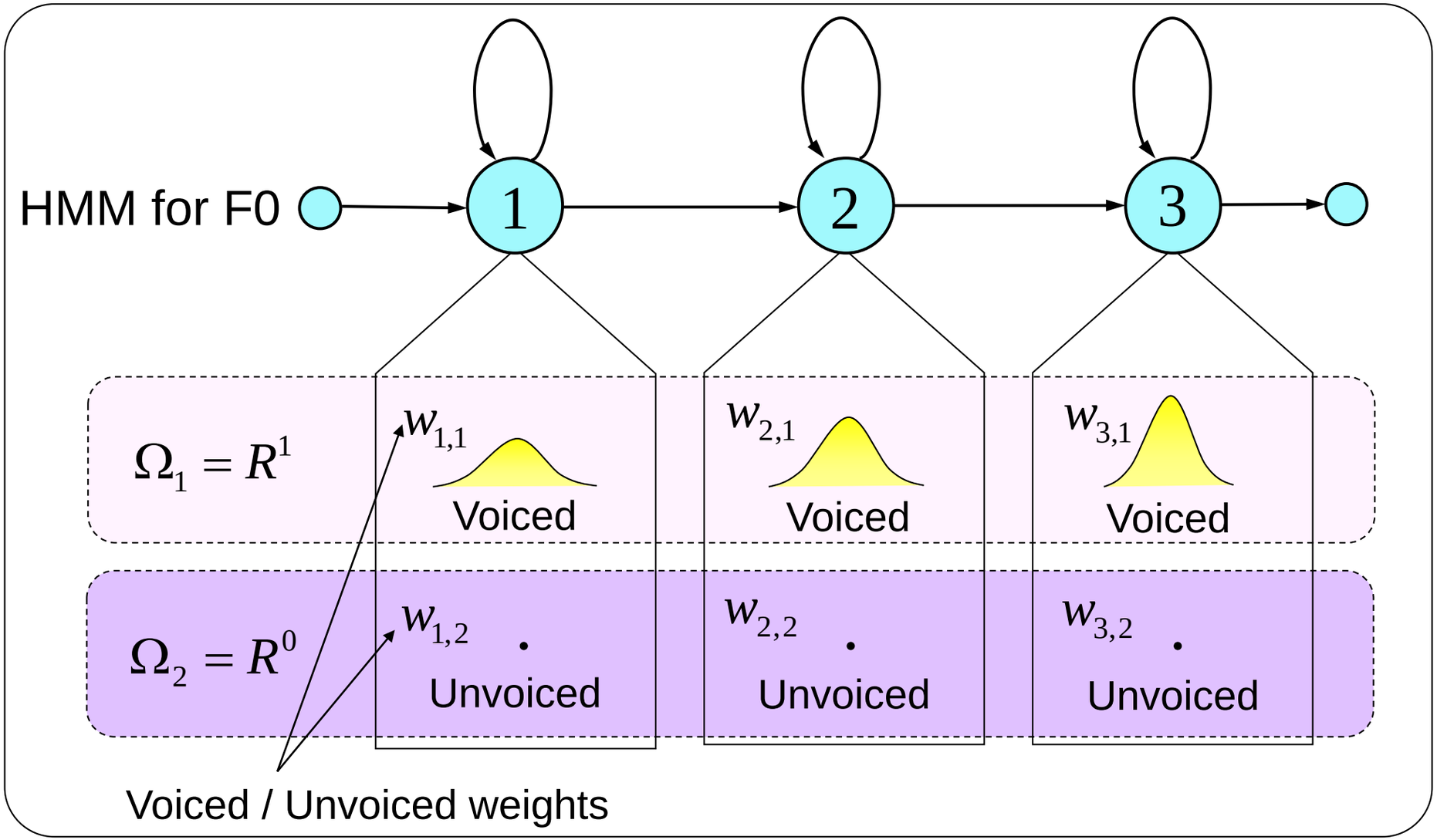
⇒ Multi-space probability distribution HMM (MSD-HMM)

Structure of MSD-HMM

Each state has two or more distributions

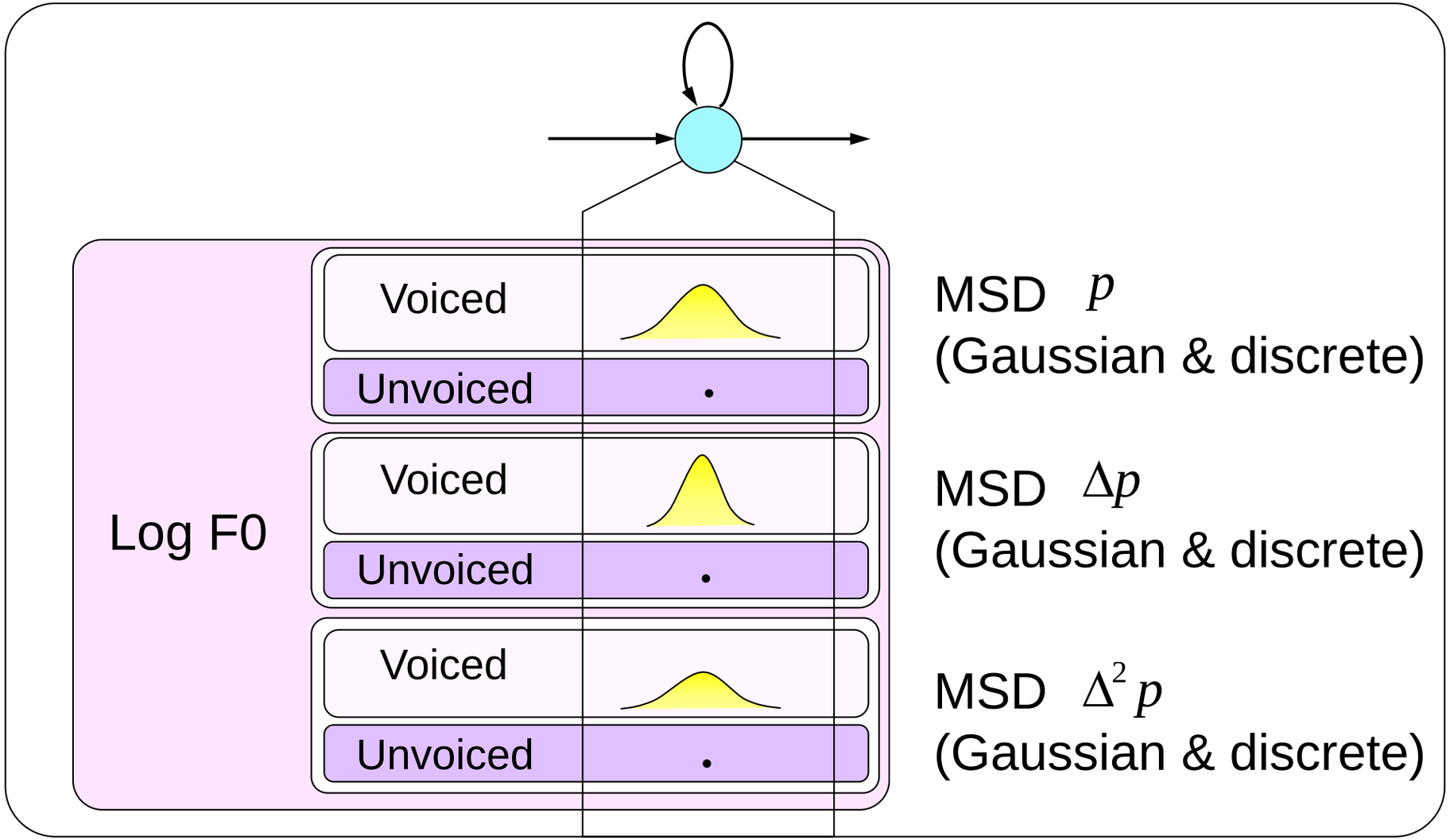


MSD-HMM for F0 Modeling

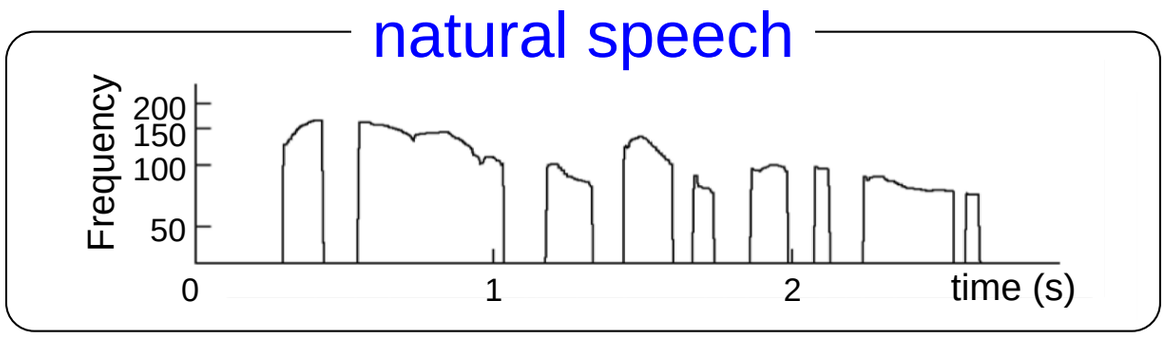


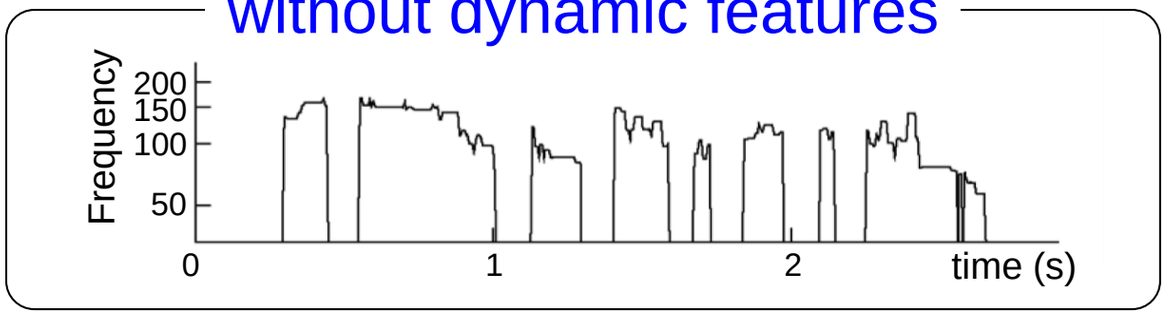
To Model Dynamic F0 Features

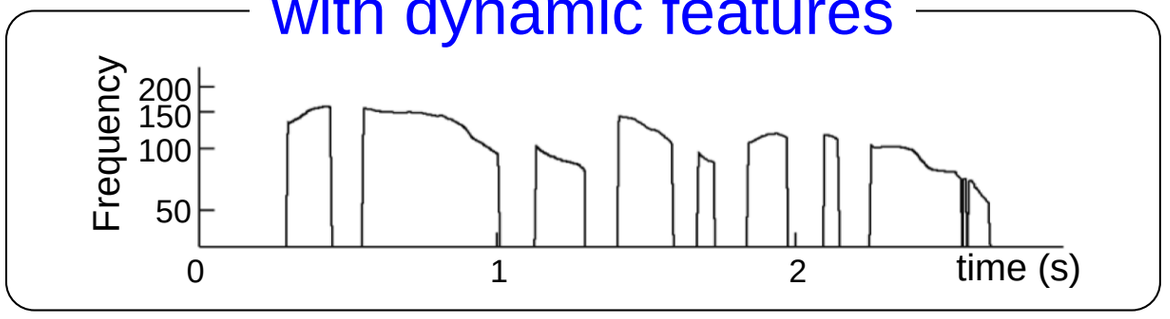
- **Structure of F0 state-output distributions**



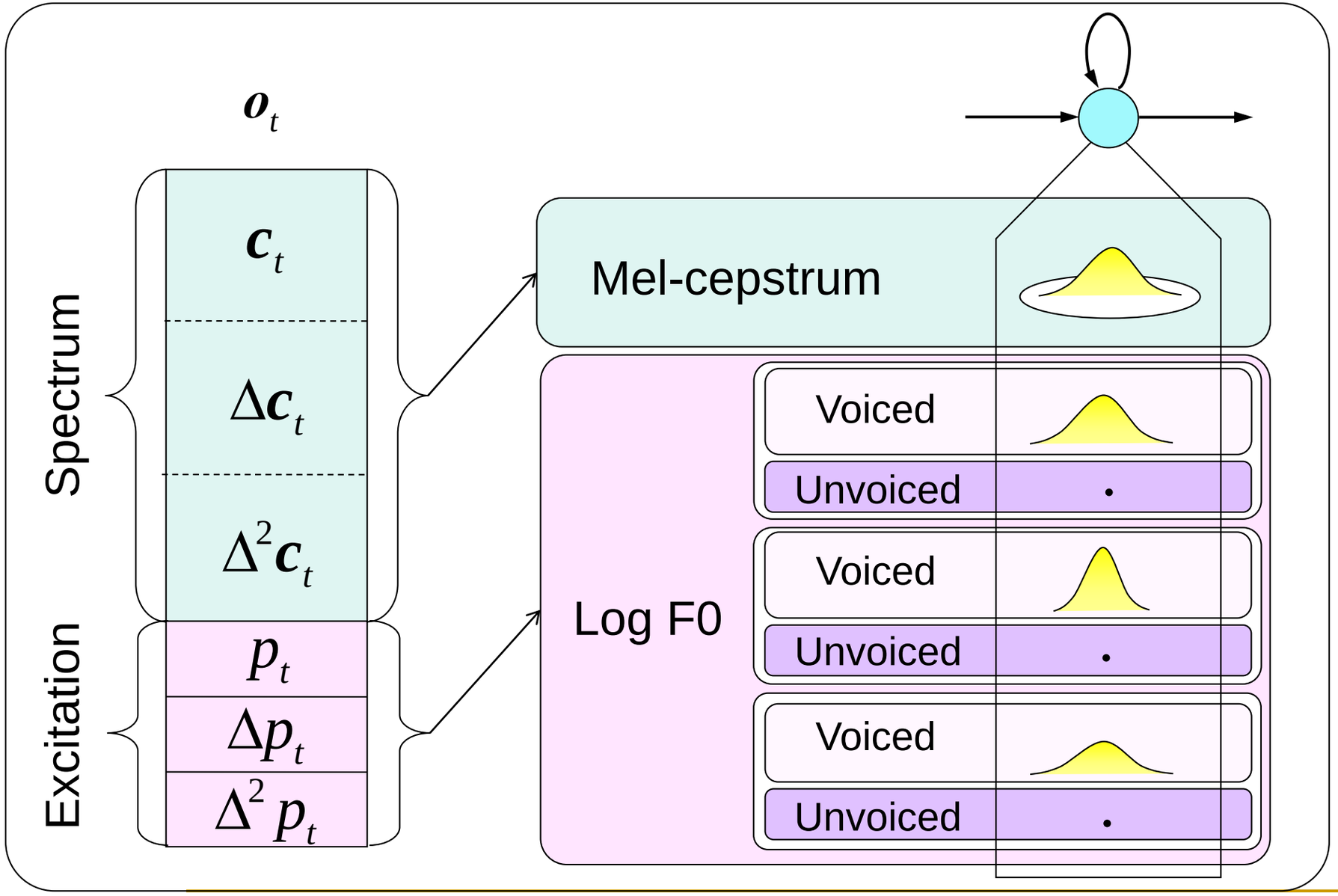
Generated F0 Trajectory







To Summarize: Structure of State-Output Distribution



To Summarize: Speech Samples (Japanese)

		Mel-cepstrum		
		static	static + Δ	static+ $\Delta + \Delta^2$
log F0	static			
	static + Δ			
	static + $\Delta + \Delta^2$			

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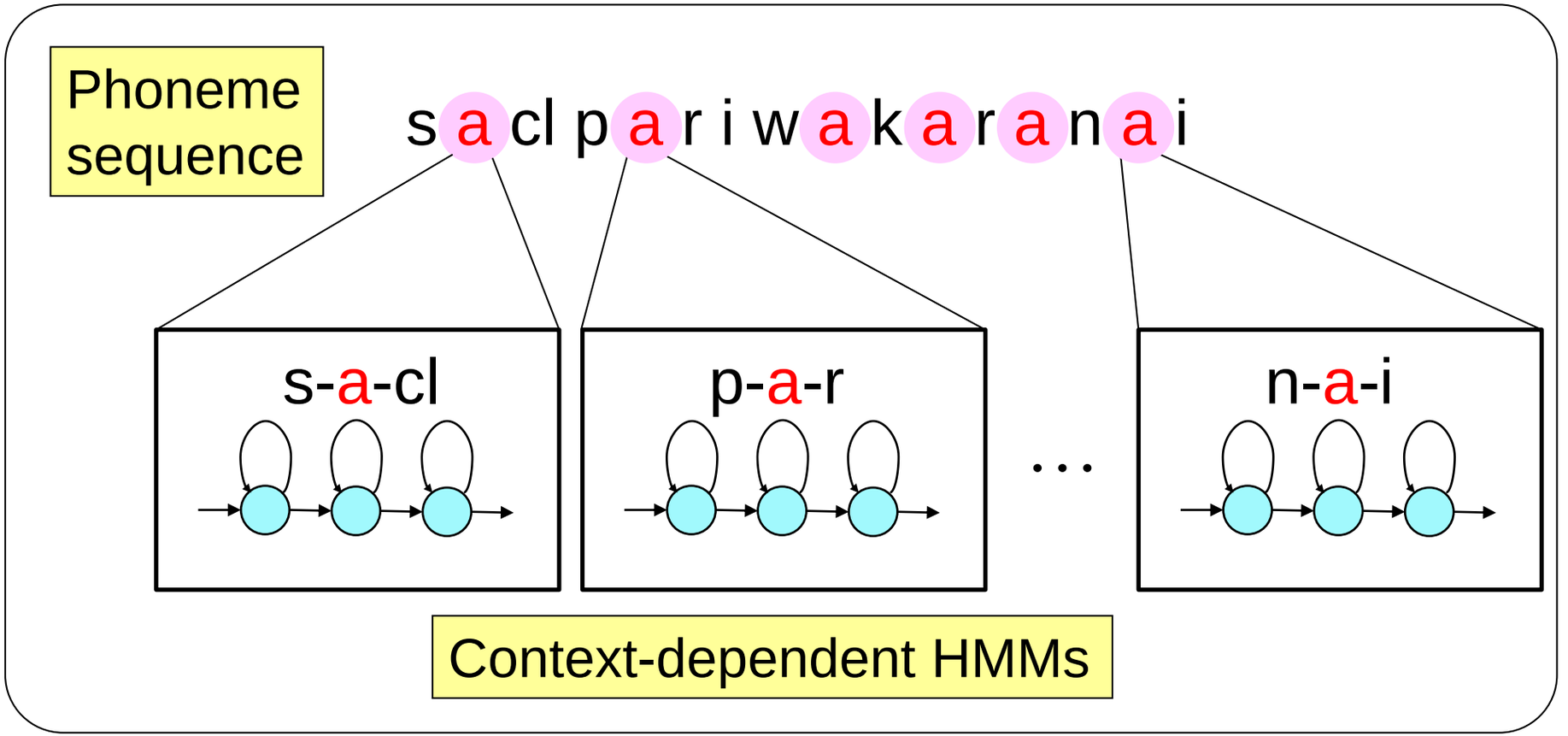
Context-Dependent Model



- **Considering relations between phonemes**
  - Context ⇒ factor of speech variations
  - Improving model accuracy

Context-Dependent Modeling

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Phoneme

- {preceding, succeeding} two phonemes
- current phoneme

Syllable

- # of phonemes at {preceding, current, succeeding} syllable
- {accent, stress} of {preceding, current, succeeding} syllable
- Position of current syllable in current word
- # of {preceding, succeeding} {accented, stressed} syllable in current phrase
- # of syllables {from previous, to next} {accented, stressed} syllable
- Vowel within current syllable

Word

- Part of speech of {preceding, current, succeeding} word
- # of syllables in {preceding, current, succeeding} word
- Position of current word in current phrase
- # of {preceding, succeeding} content words in current phrase
- # of words {from previous, to next} content word

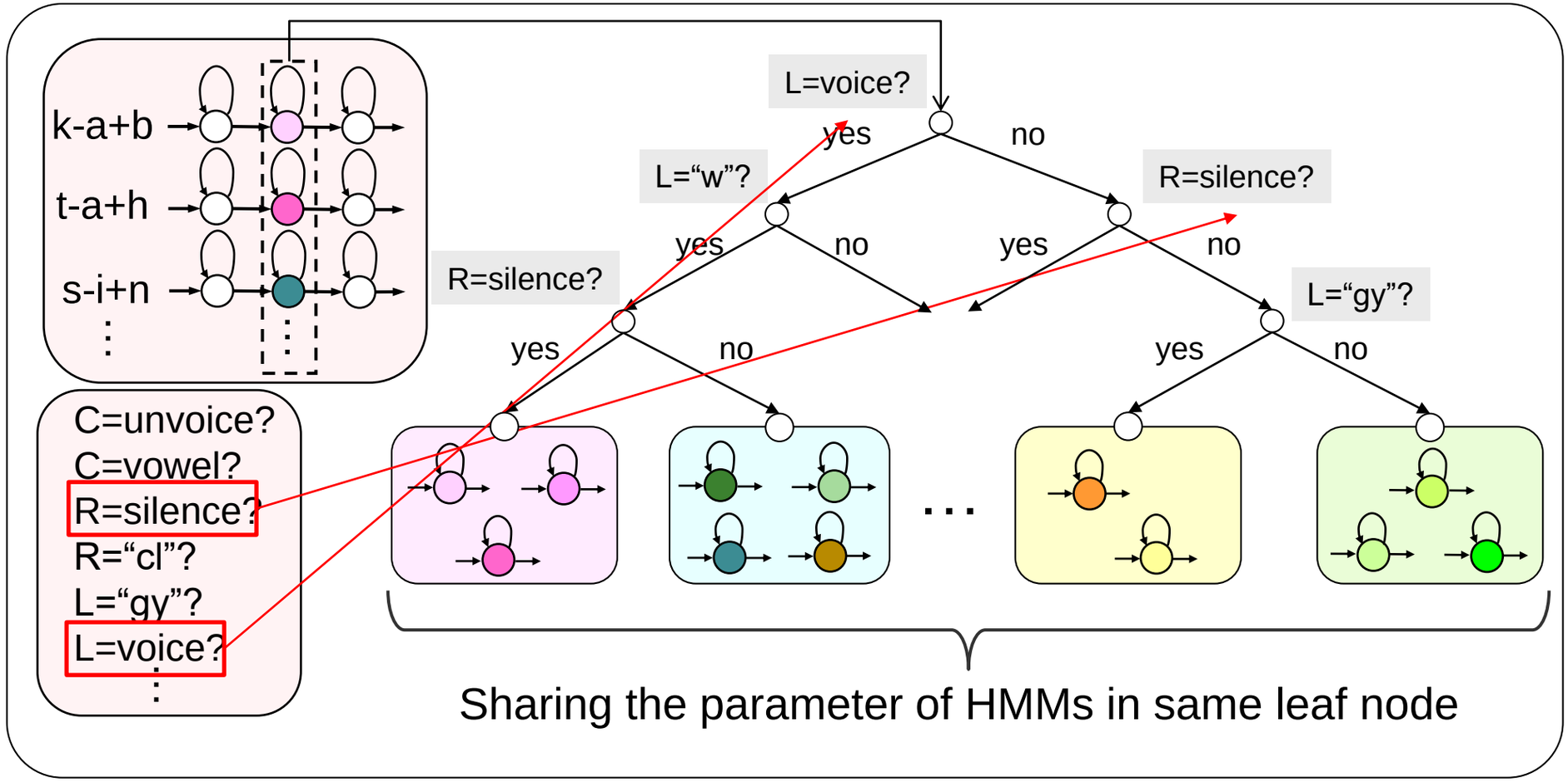
Phrase

- # of syllables in {preceding, current, succeeding} phrase

…..

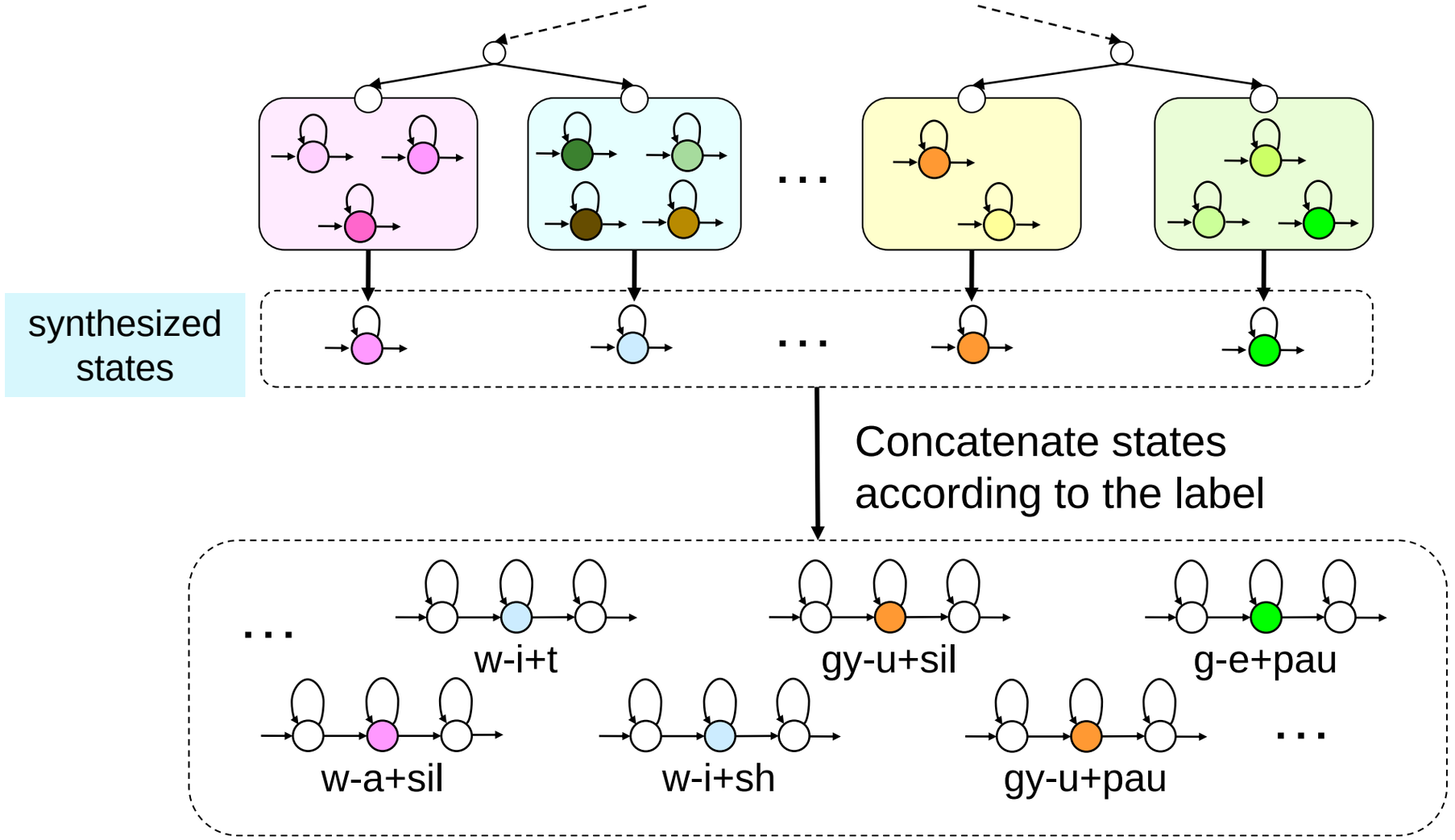
Huge # of combinations ⇒ Difficult to have all possible models

Decision Tree-based State Clustering [Odell; '95]

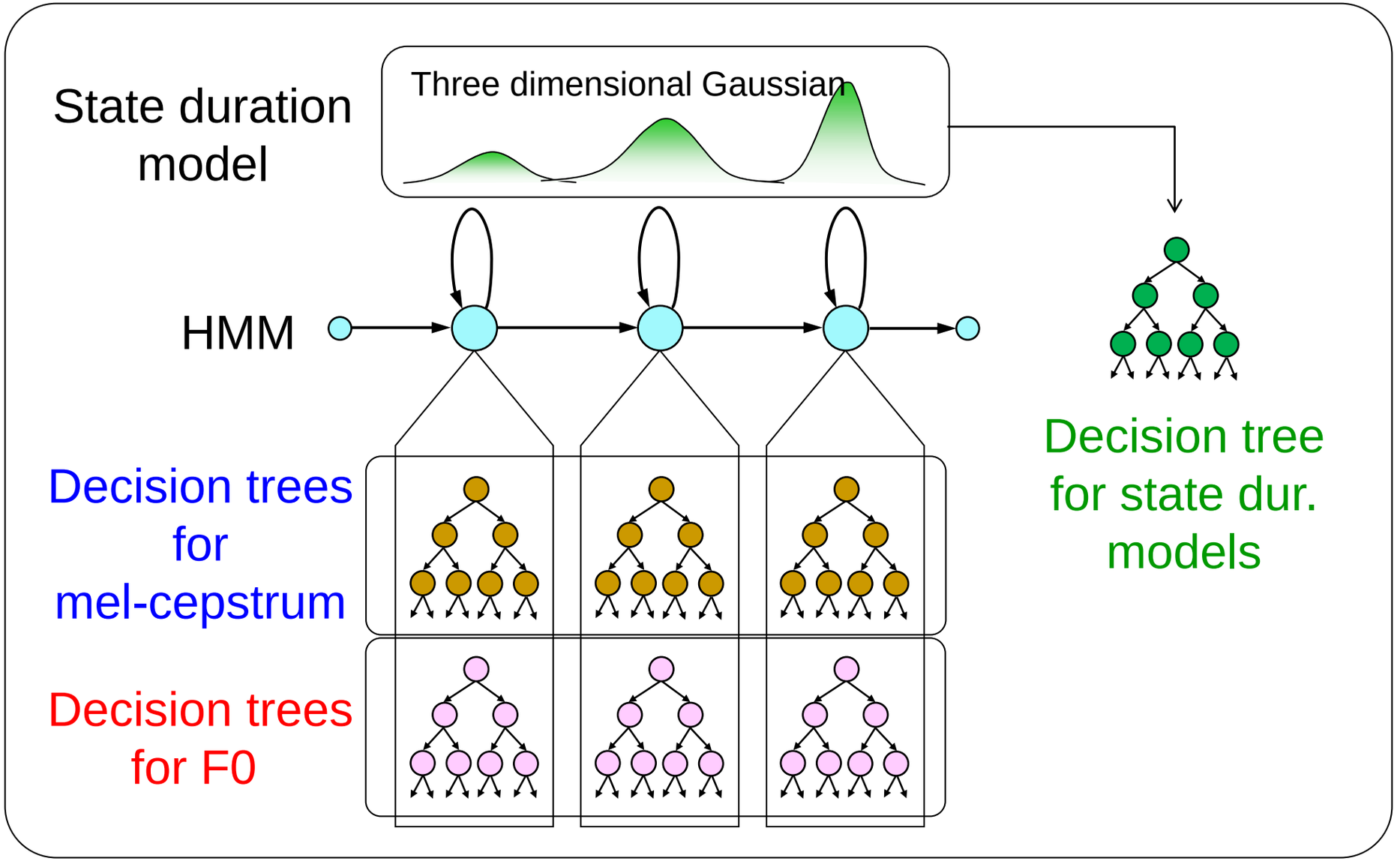


– Each state separated automatically by the optimum question
– The optimum question determined for increasing likelihood

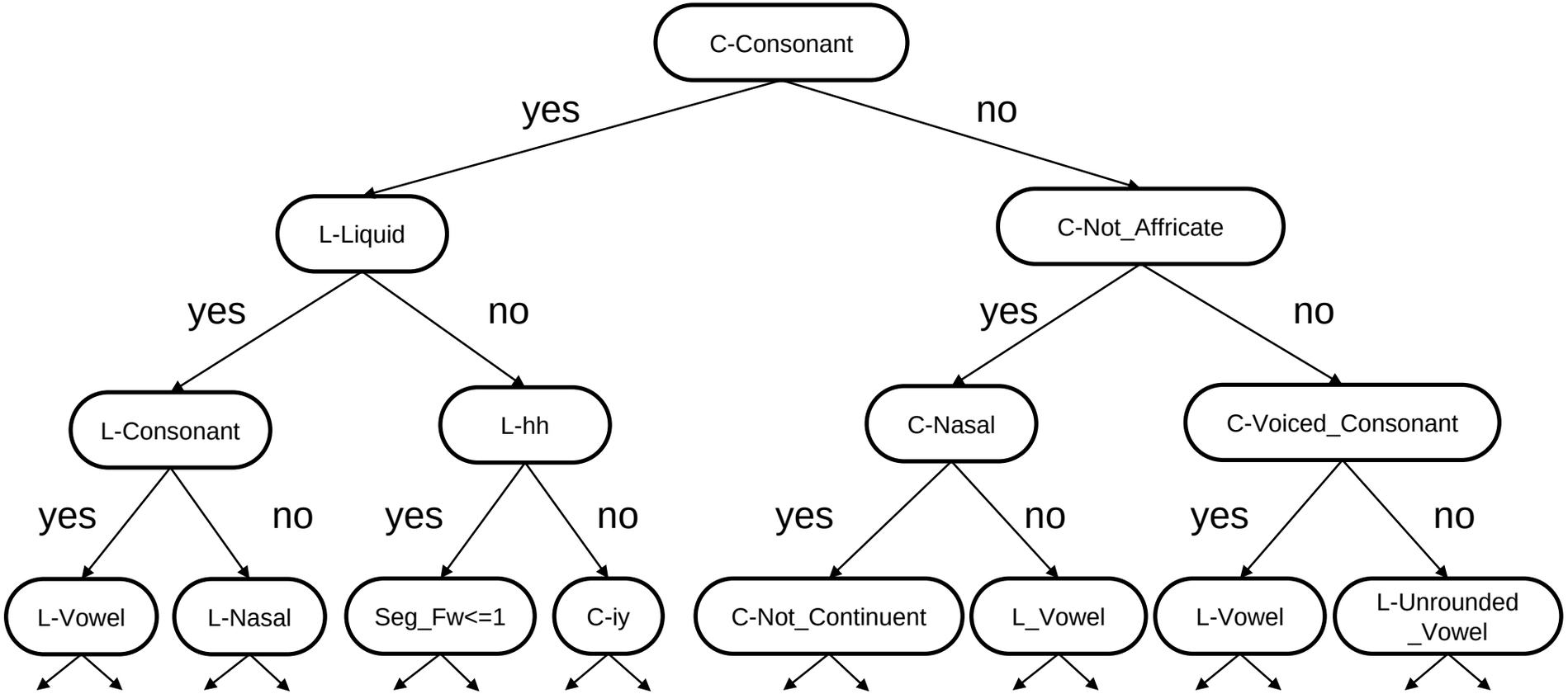
Synthesize From Leaf Nodes



Stream-dependent Tree-based Clustering

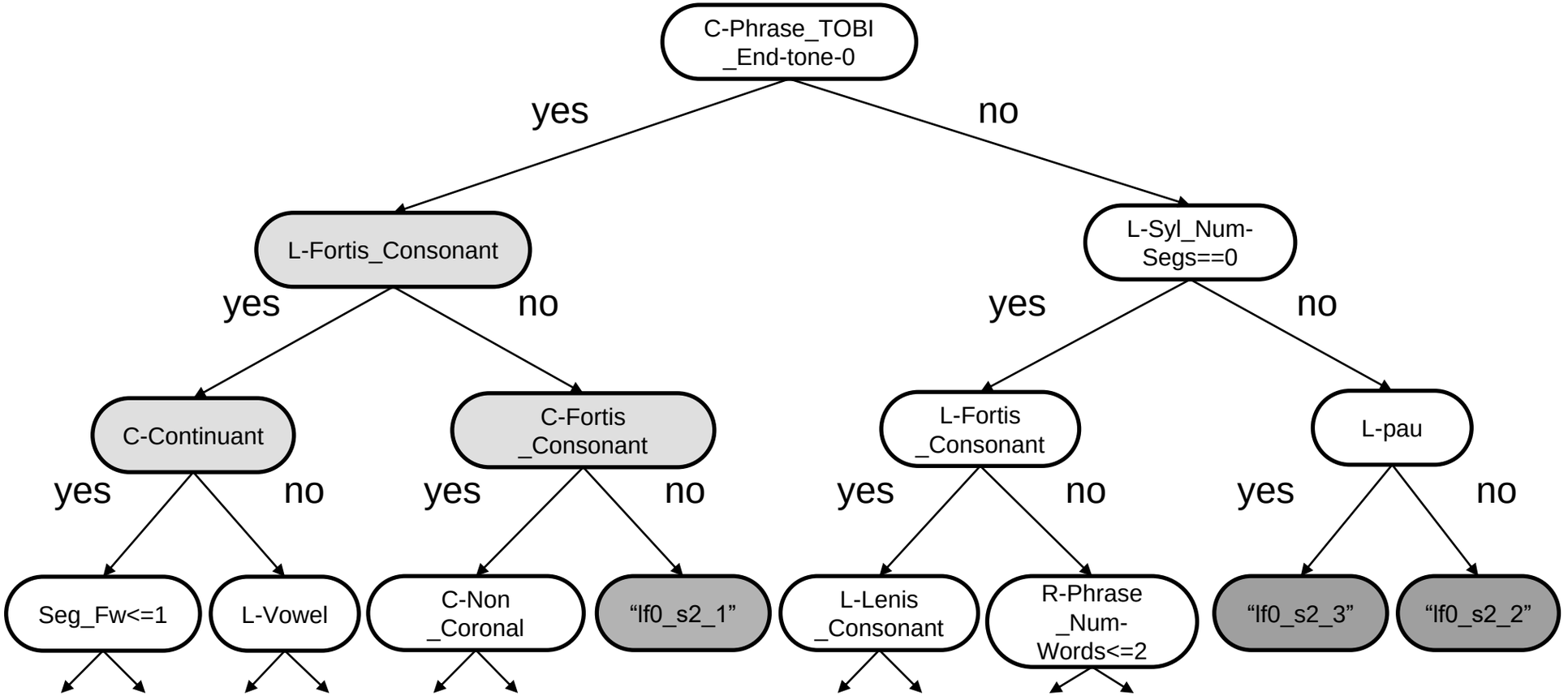


Tree for Spectrum (1st state)



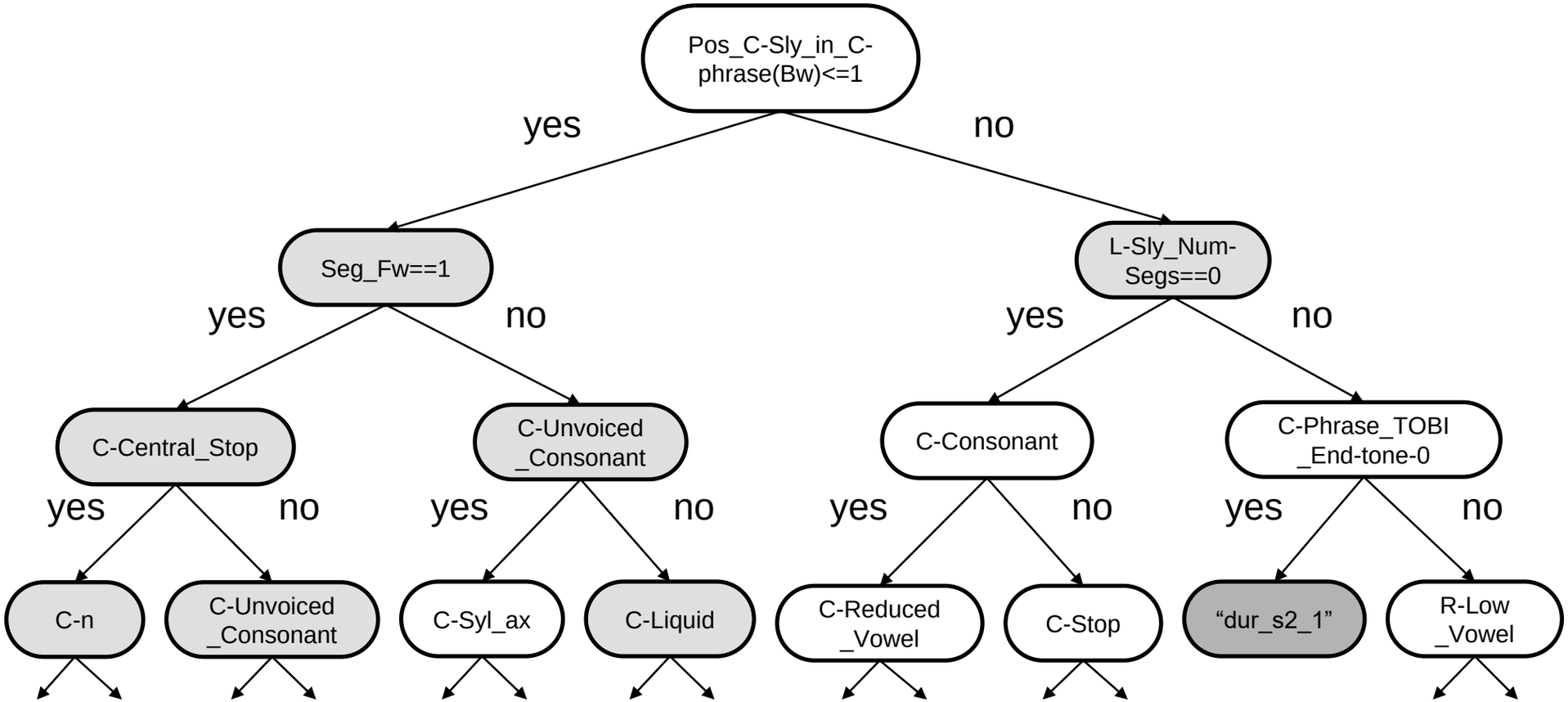
- Questions about phonetic attributes

Tree for F0 (1st state)



– Questions about linguistic attributes

Tree for State Duration

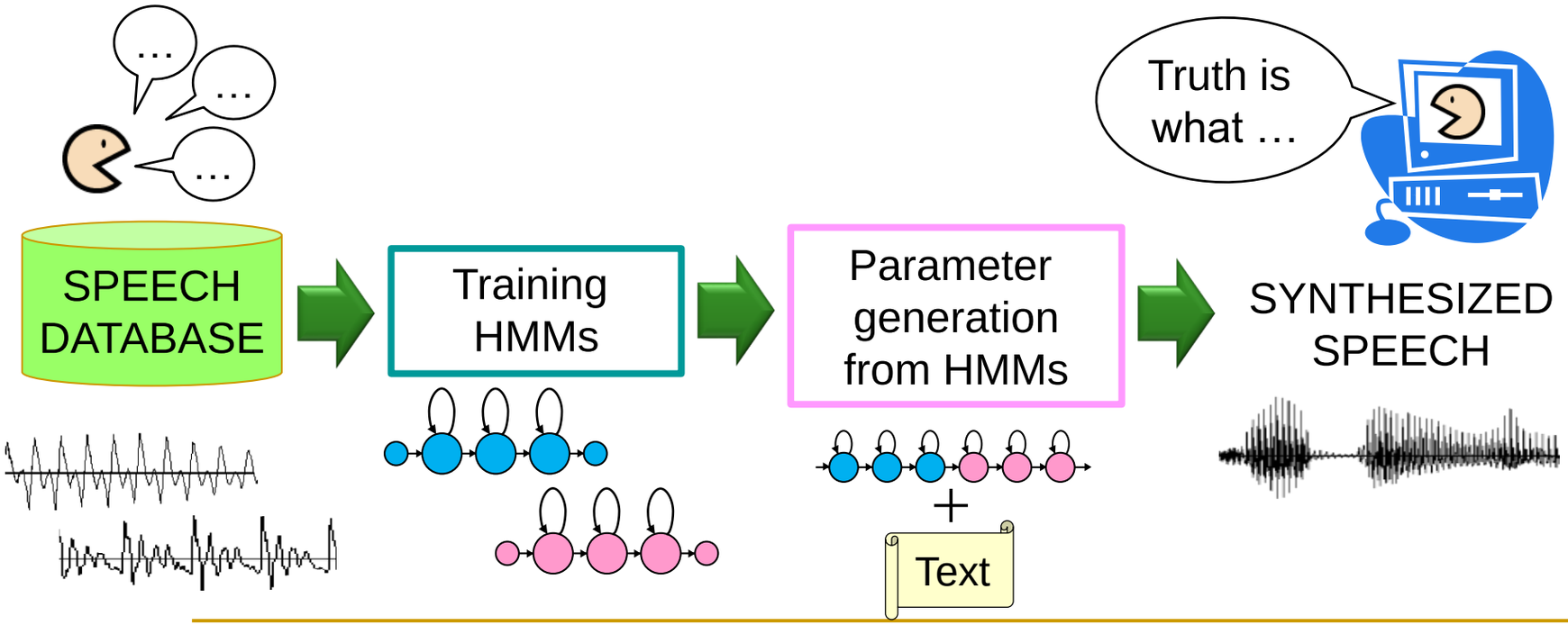


- Linguistic questions for pause
- Phonetic questions for speech

Speech Synthesis from HMM

- **Speech parameters are generated from HMMs**
  - Spectrum parameters
  - Excitation parameters (F0)
- **Vocoding parameters to synthesize speech**

  ⇒ Obtain high-quality synthesized speech

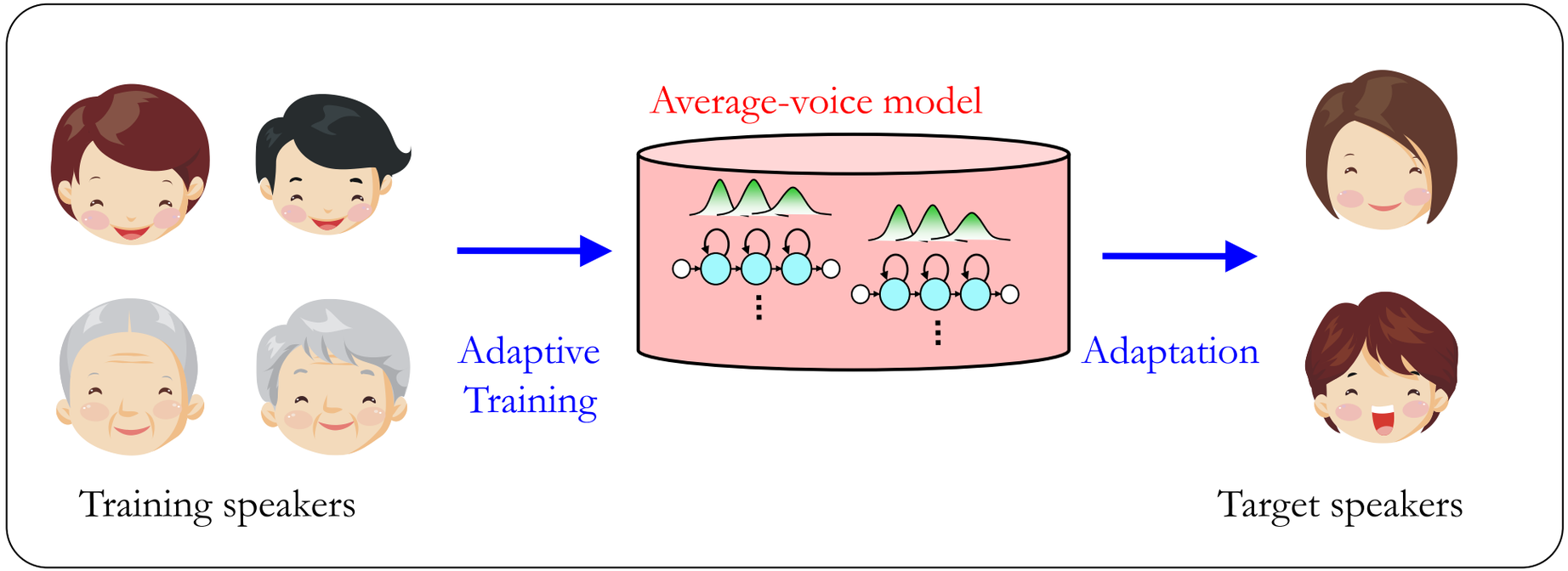


Outlines

- **Speech vocoding: Source-filter model**
- **Speech parameter modeling and generation with HMM**
  - Overview of HMM framework
  - State duration modeling
  - Spectrum modeling
  - F0 modeling
  - Context clustering
- **Voice character controlling**
  - Adaptation (mimicking voices)
  - Interpolation (mixing voices)
- **Application**
  - Singing voice
  - Emotional voice
  - Audio-visual speech synthesis

Adaptation (Mimicking Voices)

- **Adaptation / adaptive training of HMMs**
  - Originally developed in ASR, but works very well in TTS
  - Average voice-based speech synthesis (AVSS) [Yamagishi; '06]



– Require small data of target speaker / speaking style

⇒ small cost to create new voices

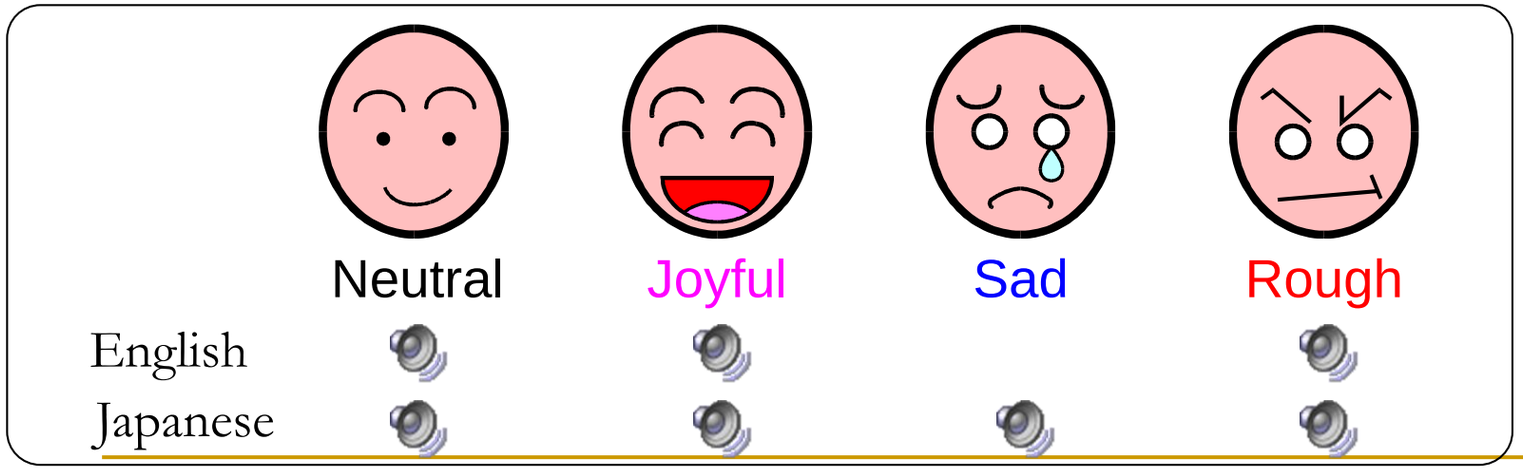
Adaptation Demo

- **Speaker adaptation**

  Original voice:

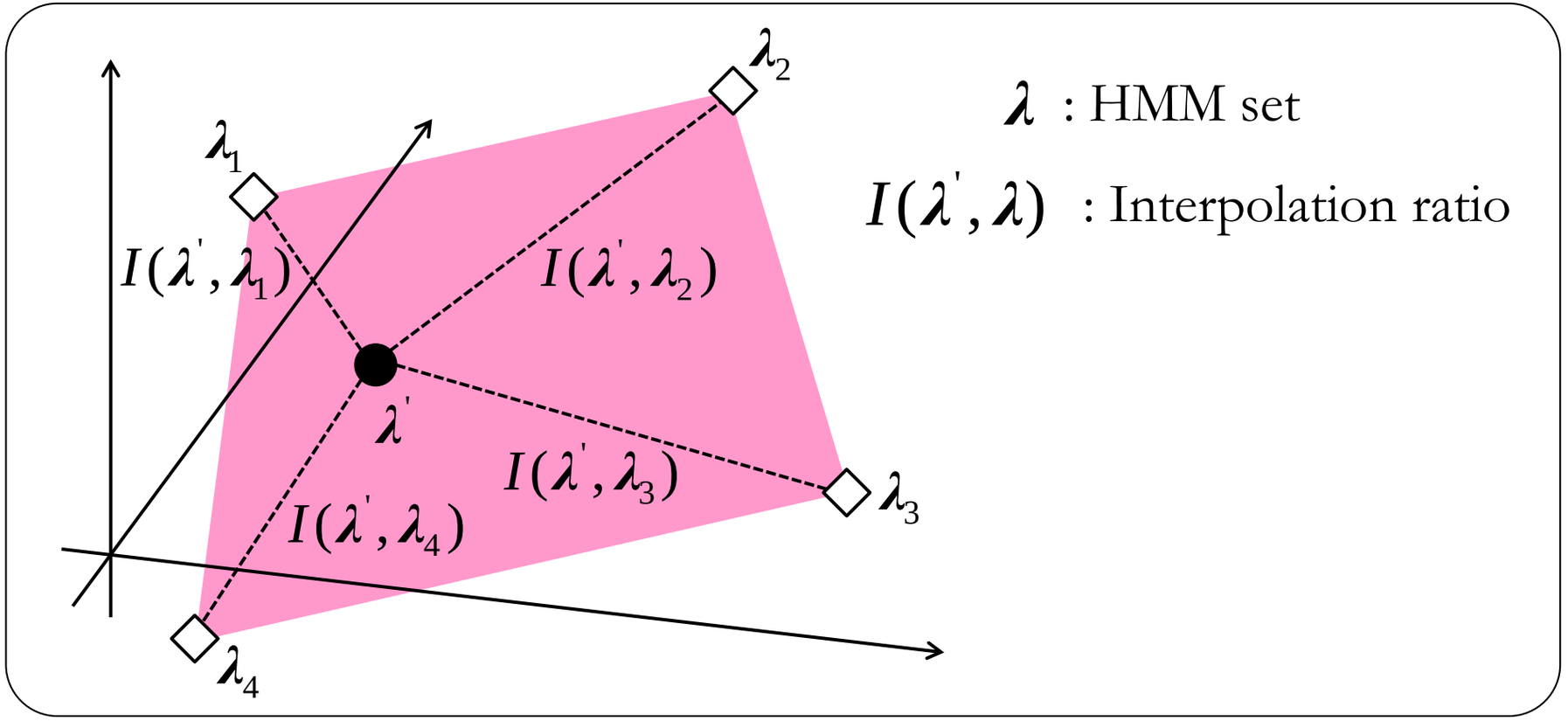
Average voice model	Number of adaptation sentences			
	10 sentences	100 sentences	500 sentences	1132 sentences

- **Style adaptation**



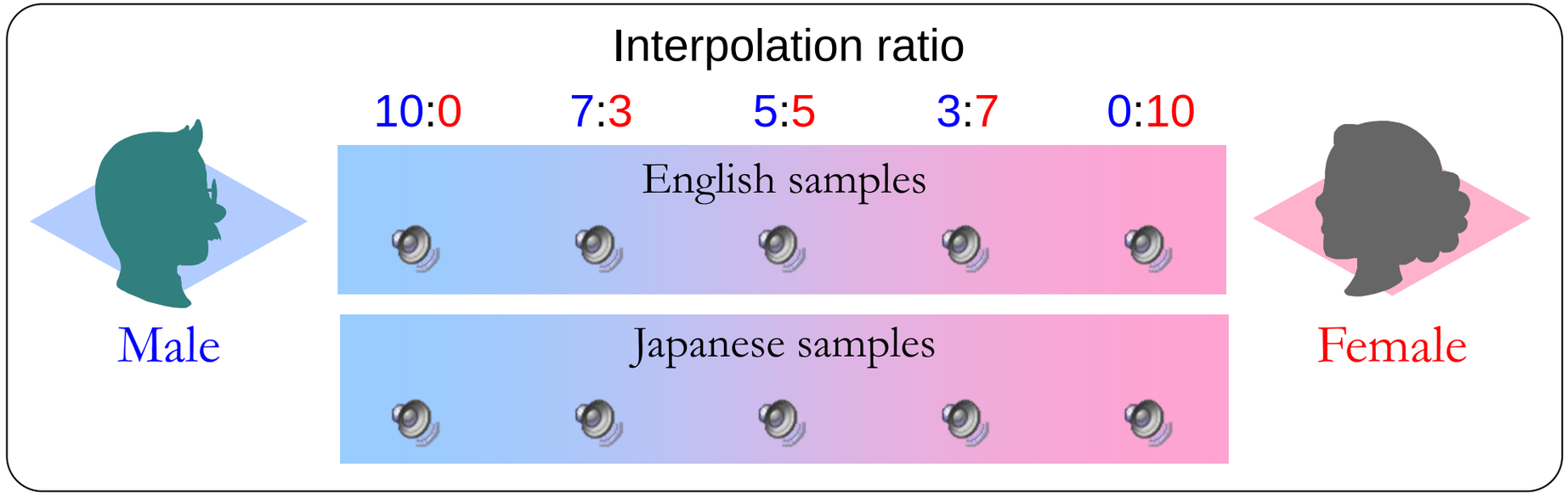
Interpolation (Mixing Voices)

- **Interpolate parameters among representative HMM sets**
  - Create new voices even if no adaptation data is available
  - Gradually change speaker & speaking styles [Yoshimura; ’97, Tachibana; ’05]

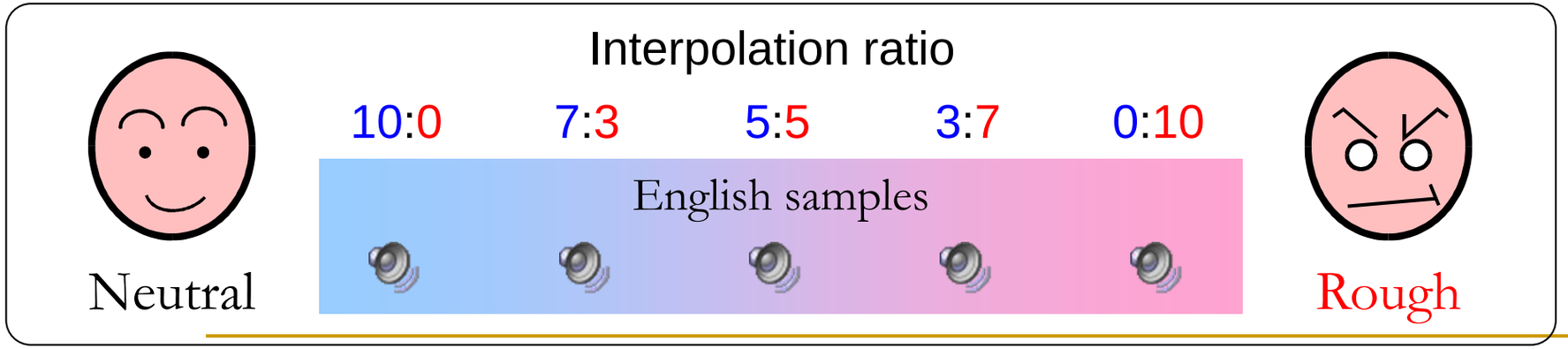


Interpolation Demo

- **Speaker interpolation**



- **Style interpolation**



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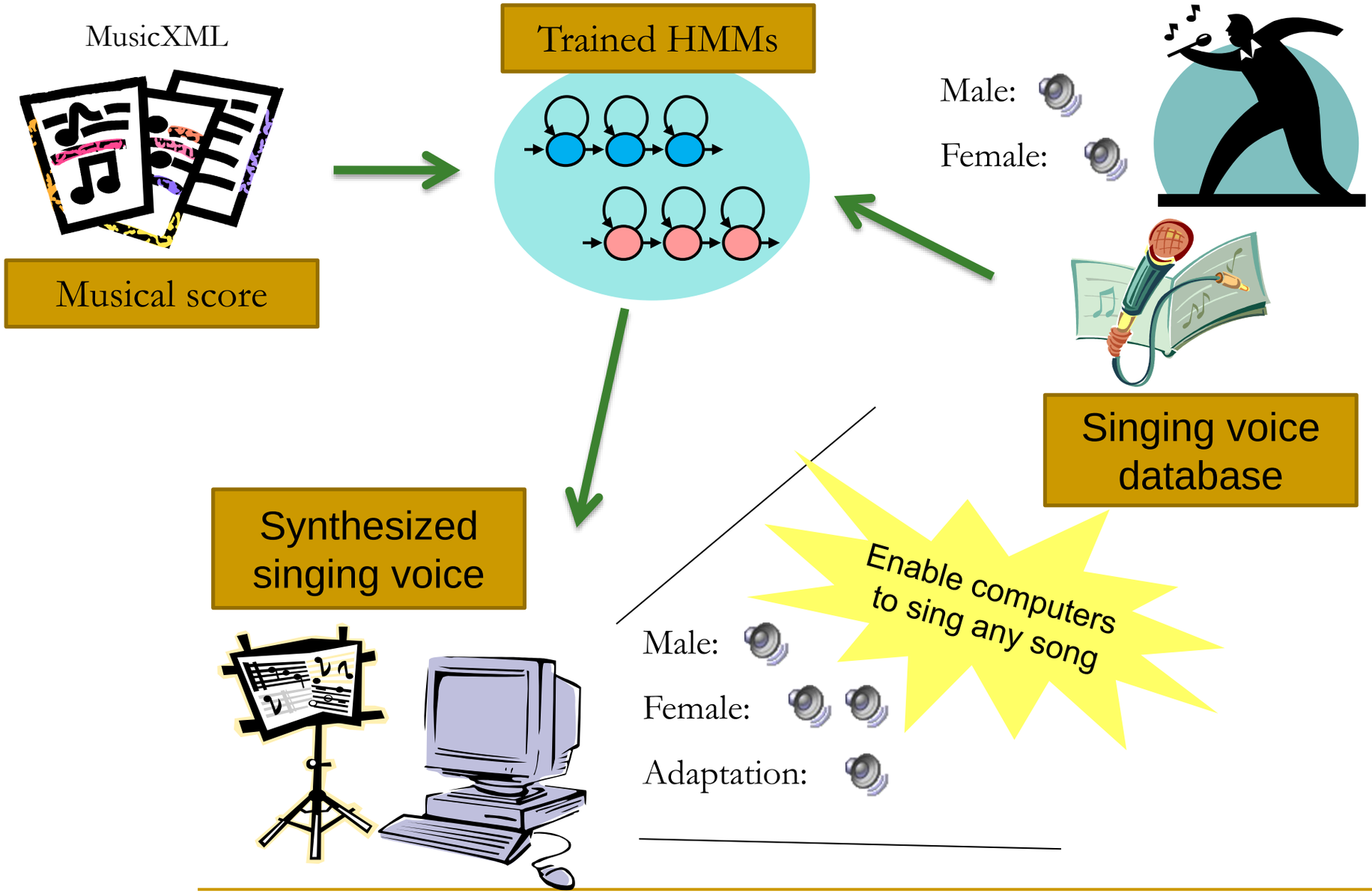
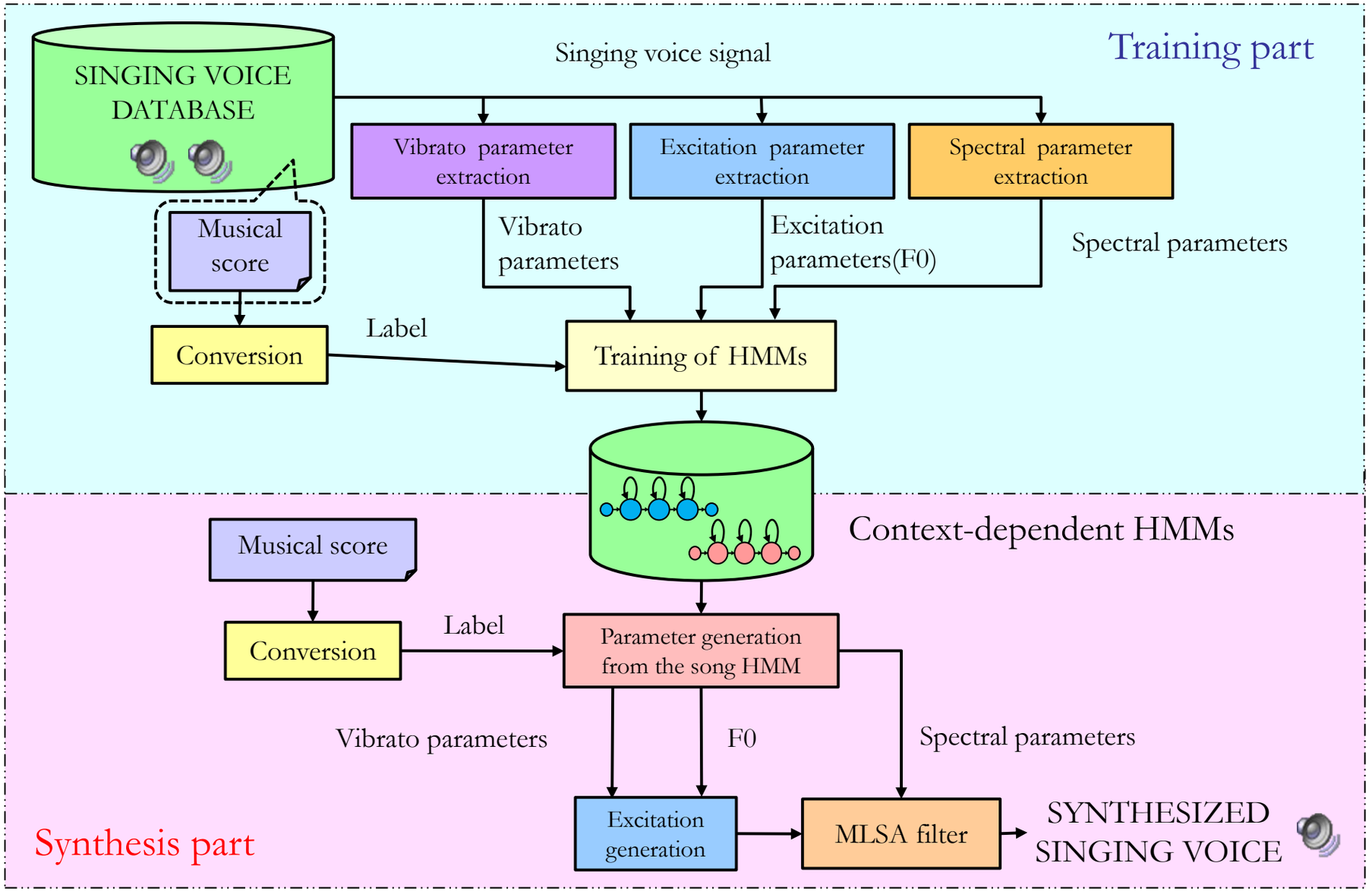
Singing Voice Synthesis [Oura; '10]

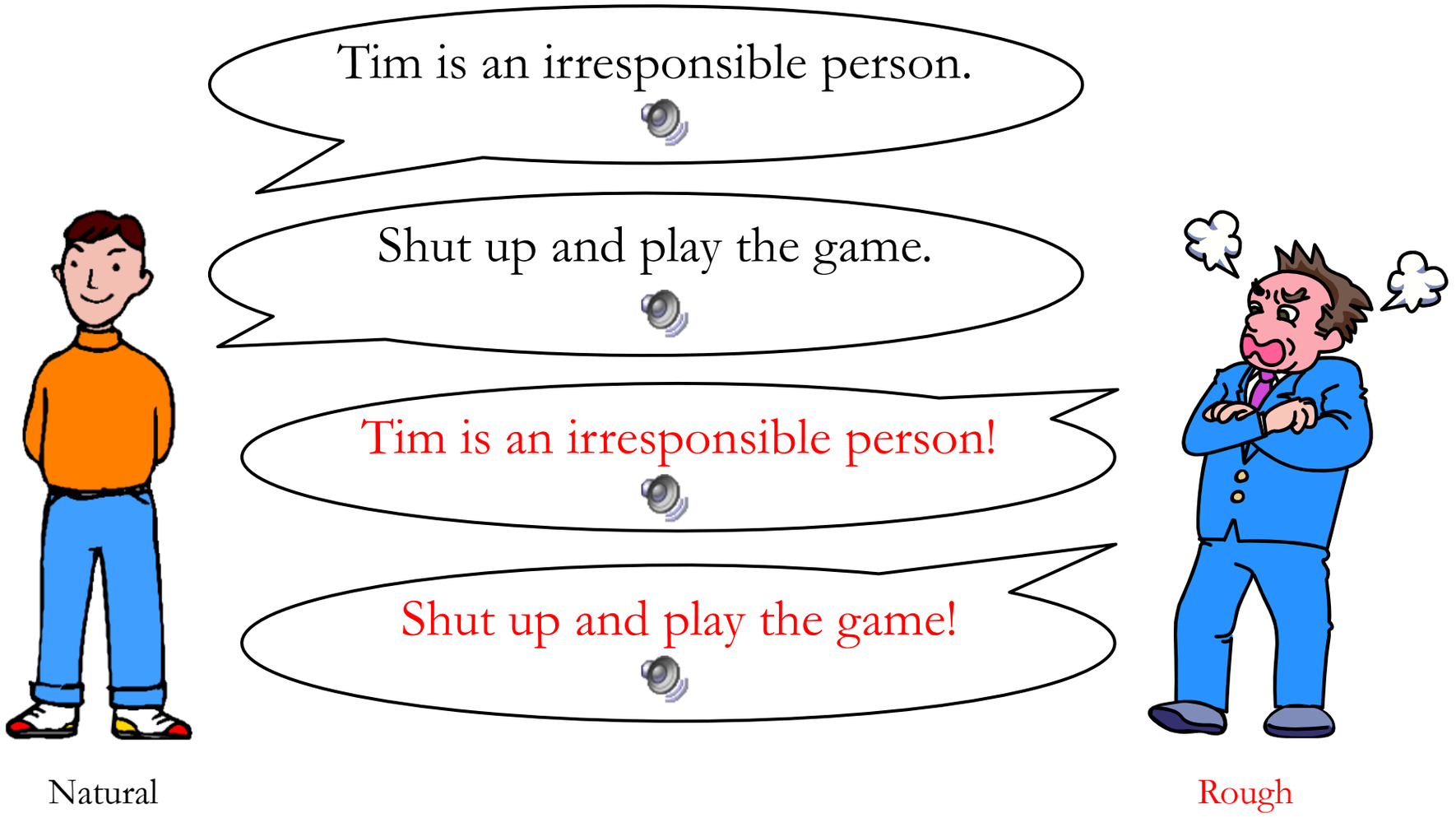


Singing Voice Synthesis



Emotional Speech Synthesis [Tsuzuki; '04]

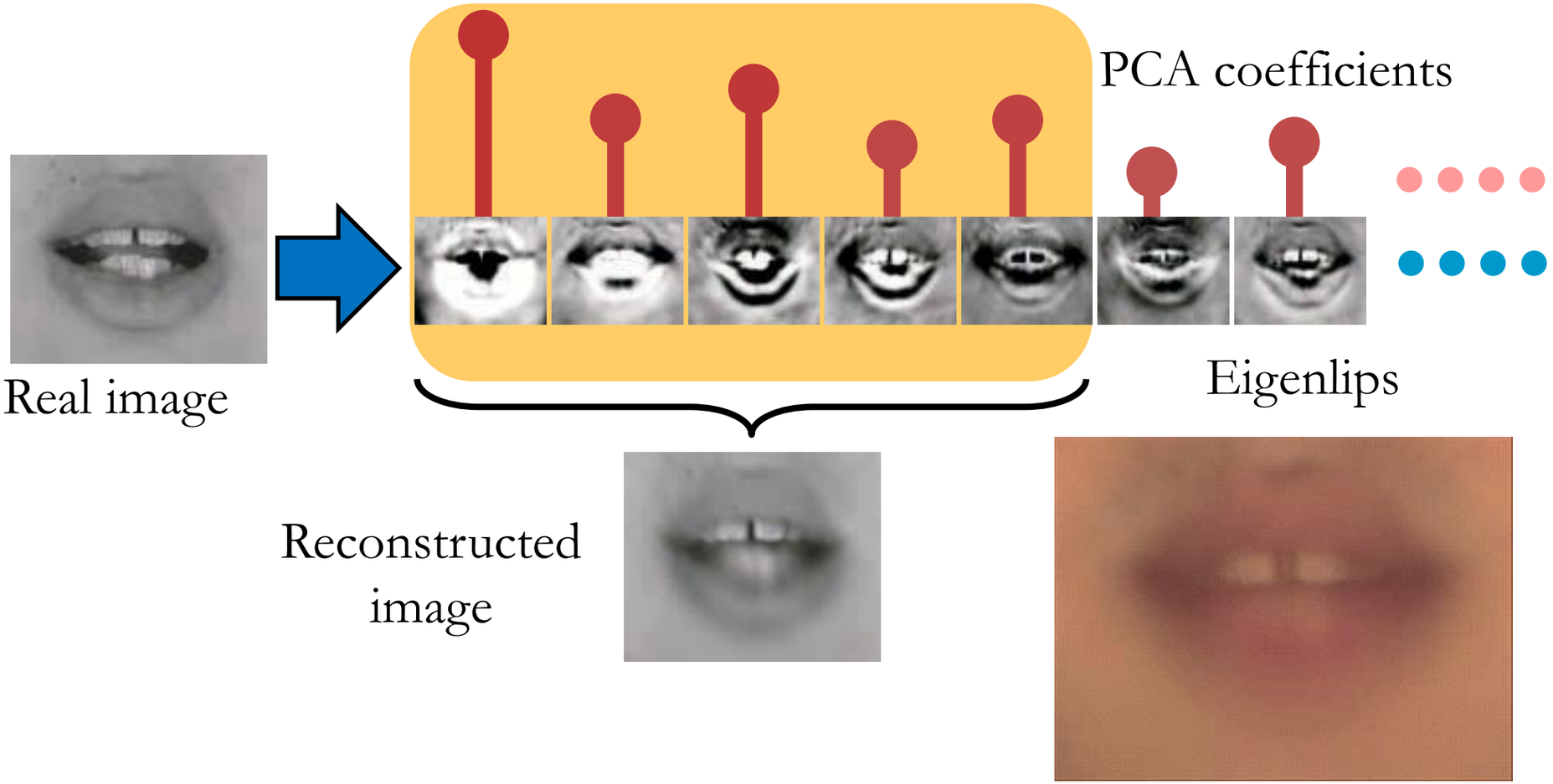
Using emotional voices for training data



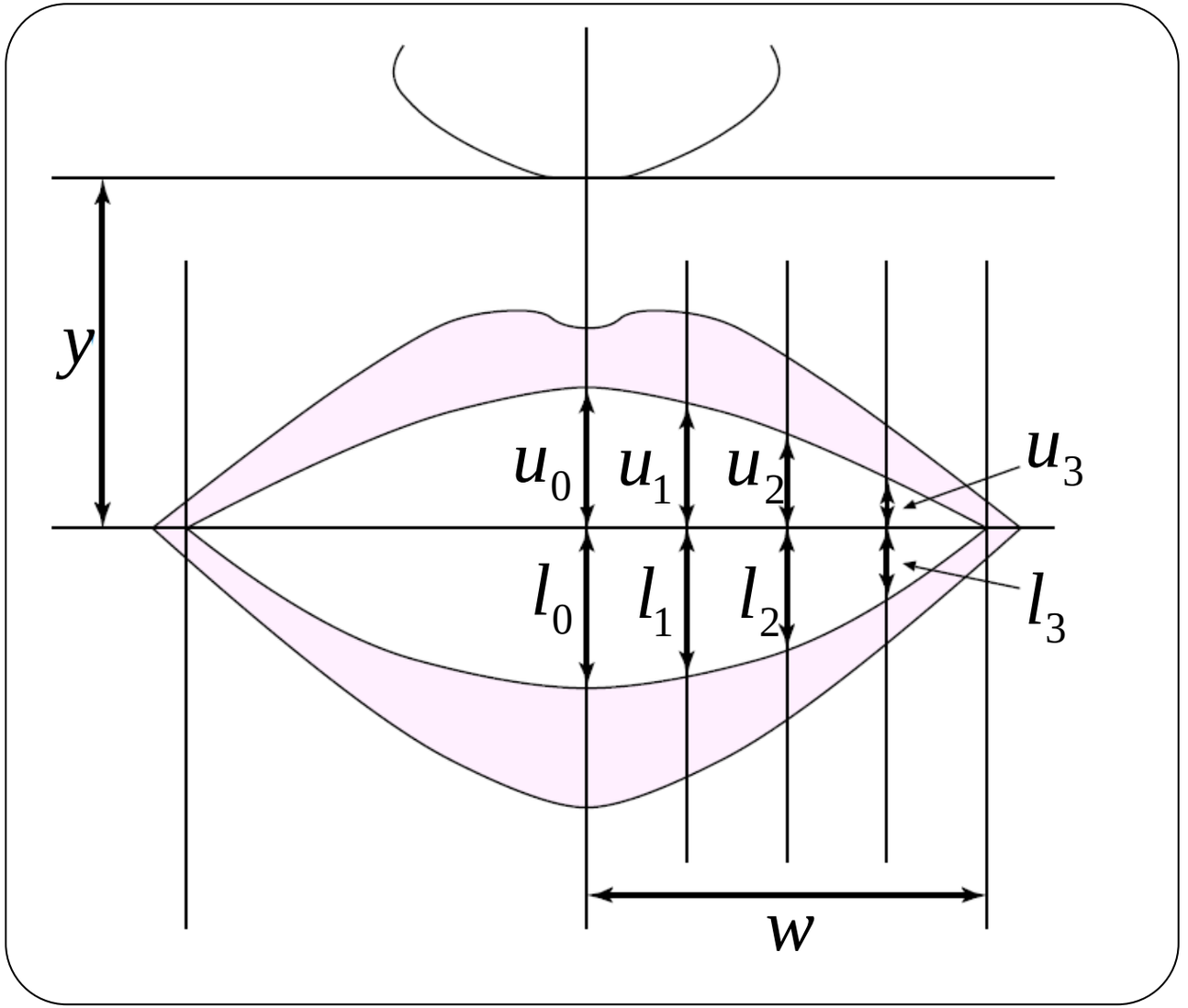
Audio-Visual Synthesis (Pixel-based) [Sako; '00]

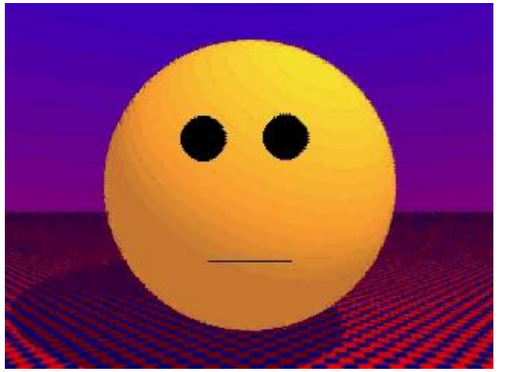
- **Pixel image: high dimensionality**

  ⇒Dimensionality reduction by PCA



Audio-Visual Synthesis (Model-based) [Tamura; '98]





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