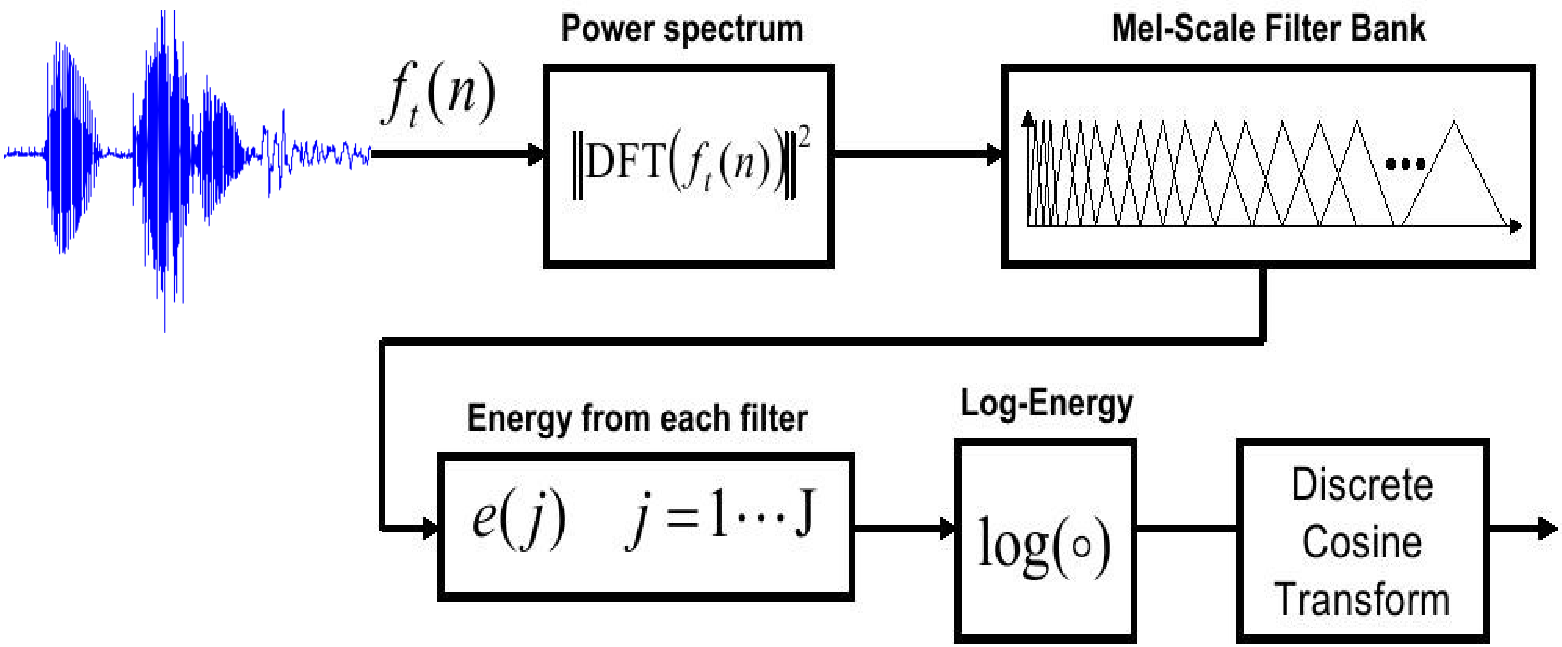
Timeline in the course

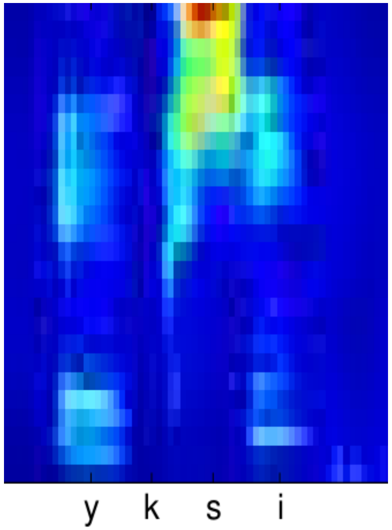
	Meetings Wednesdays	Thursdays or Fridays	Home exercises	Project work status
Week1 Oct 28-30	Speech features entry test	Classification	Feature classifier	Literature study Meet tutors Oct 28
Week2 Nov 4-6	Phoneme modeling	Recognition	Word recognizer	Work plan Meet tutors Nov 4
Week3 Nov 11-13	Lexicon and language	Language model	Text predictor	Analysis Meet tutors Nov 11
Week4 Nov 18-20	Continuous speech advanced search	LVCSR	Speech recognizer	Experimentation Meet tutors Nov 18
Week5 Nov 25-27	End-to-end ASR	End-to-end	End-to-end recognizer	Preparing reports Meet tutors Nov 25
Week6 Dec 2-4	Projects1	Projects2		Presentations
Week7 Dec 9-11	Projects3	Projects4 Conclusion		Report submissio

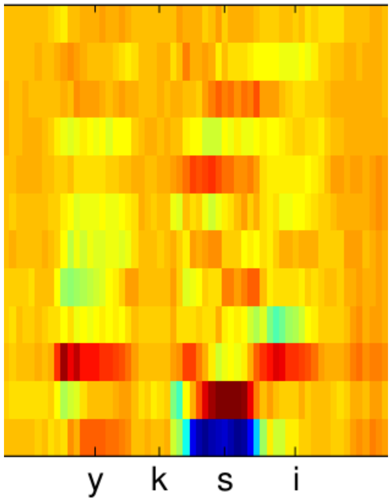
Content today

1. **Preprocessing, features, GMM**
2. Phonemes
3. HMM
4. Home exercise 2: Build a GMM-HMM system to recognize spoken words

Review: computation of MFCC







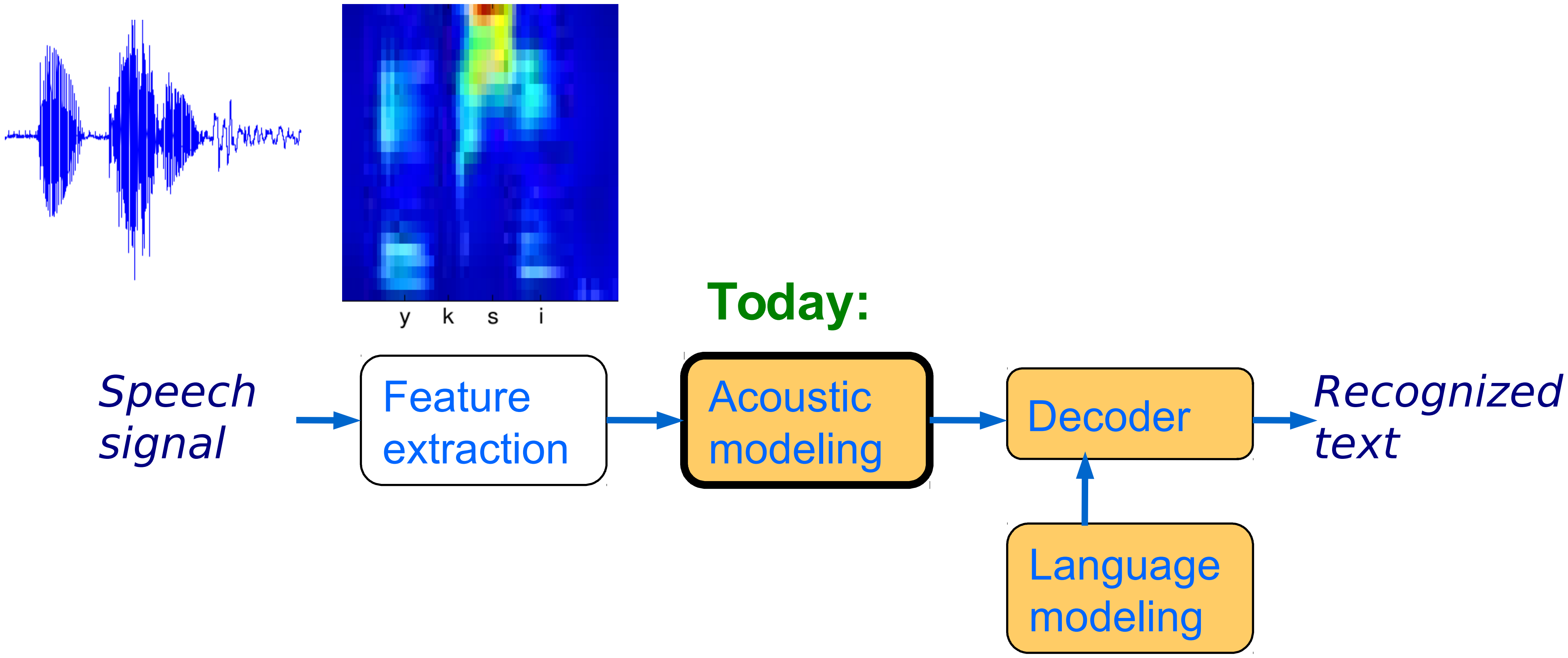

```
y = wavread('yksi.wav');

s = spectrogram(y,hamming(400),240);

spec = sqrt(abs(s));

mfcc = D*log(1+M*spec);
```

Review: speech recognition -from beginning to end



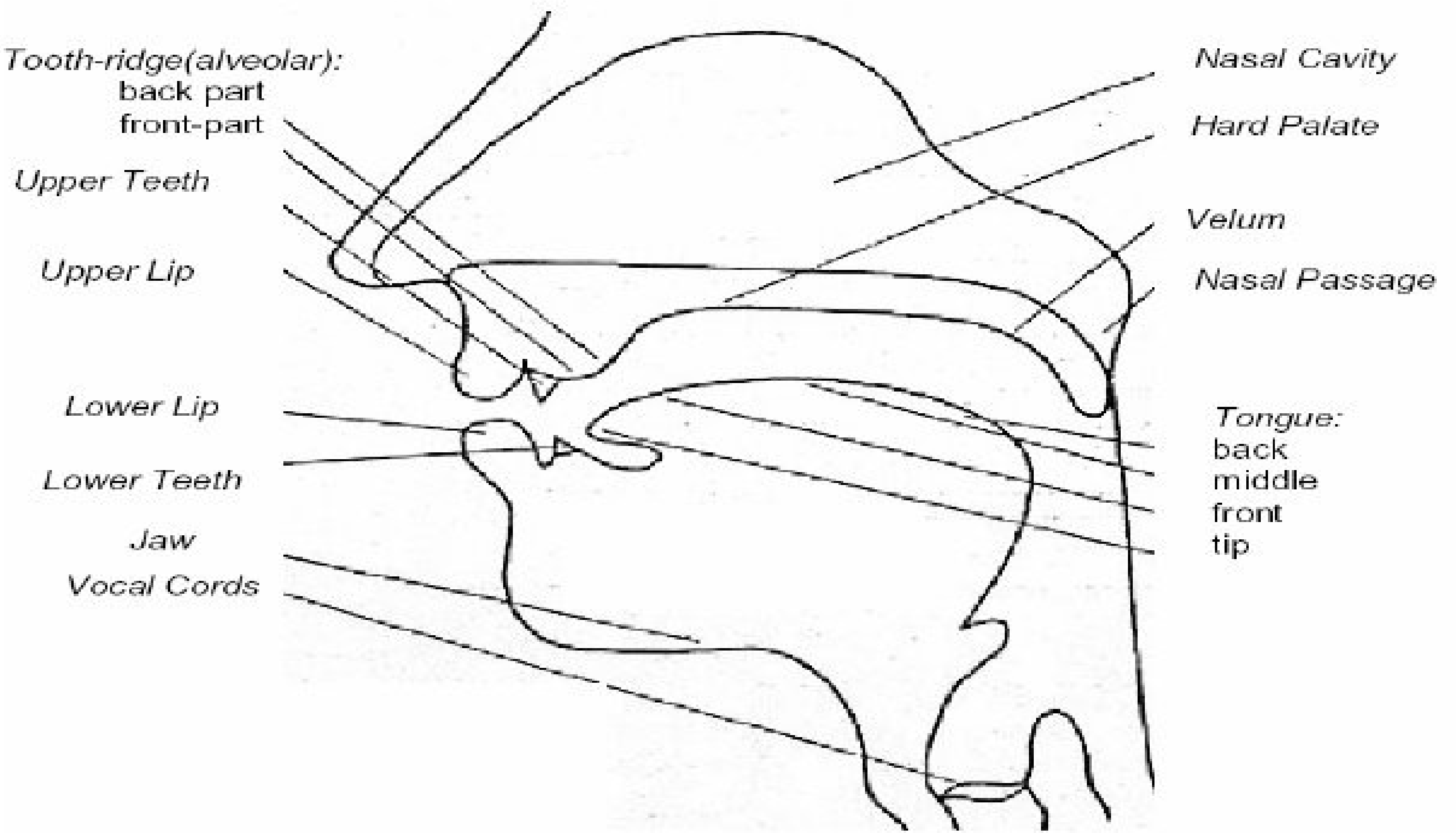
Content today

1. Preprocessing, features, GMM
2. **Phonemes**
3. HMM
4. Home exercise 2: Build a GMM-HMM system to recognize spoken words

Description of speech sounds

- **Speech can be written down** using abstract units called phonemes
- **Phonemes** describe the sounds **by the way they are produced by human**
- Main classes:
  - vowels: air flow is not obstructed
  - consonants: air flow is partially or totally obstructed
- There are different writing systems, e.g. IPA (International Phonetic Alphabet)
- The phoneme sets differ depending on language

Production of speech sounds



Picture from Huang's text book (2001)

IPA symbols for US English

PHONEME	EXAMPLE	PHONEME	EXAMPLE	PHONEME	EXAMPLE
/iʸ/	beat	/s/	see	/w/	wet
/ɪ/	bit	/š/	she	/r/	red
/eʸ/	bait	/f/	fee	/l/	let
/ɛ/	bet	/θ/	thief	/y/	yet
/æ/	bat	/z/	z	/m/	meet
/ɑ/	Bob	/ž/	Gigi	/n/	neat
/ɔ/	bought	/v/	v	/ŋ/	sing
/ʌ/	but	/ð/	thee	/c/	church
/oʷ/	boat	/p/	pea	/j/	judge
/ʊ/	book	/t/	tea	/h/	heat
/uʷ/	boot	/k/	key		
/ɝ/	Burt	/b/	bee		
/ɑʸ/	bite	/d/	Dee		
/ɔʸ/	Boyd	/g/	geese		
/ɑʷ/	bout				
/ə/	about				

Table from MIT Course Notes: 6.345 Automatic Speech Recognition, Spring 2003

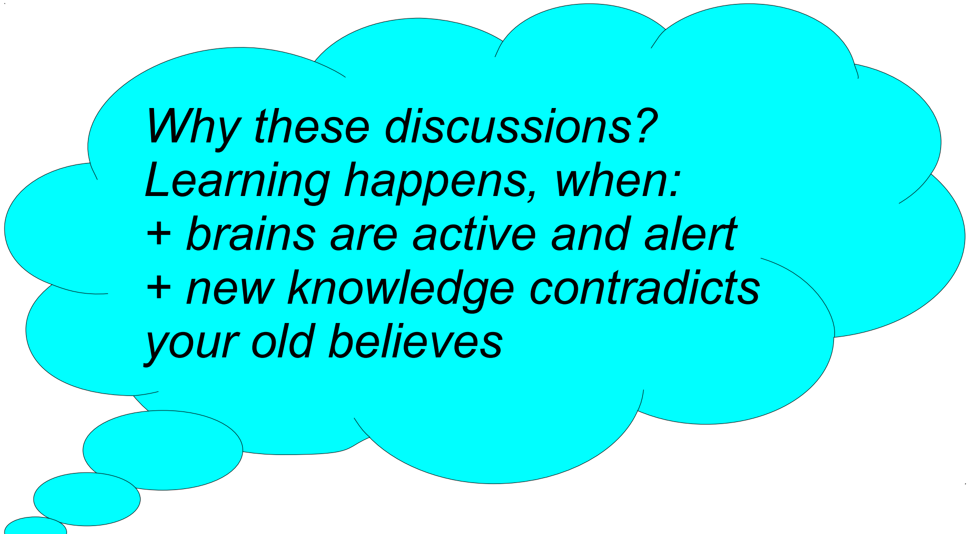
CMU Sphinx ASR system symbols

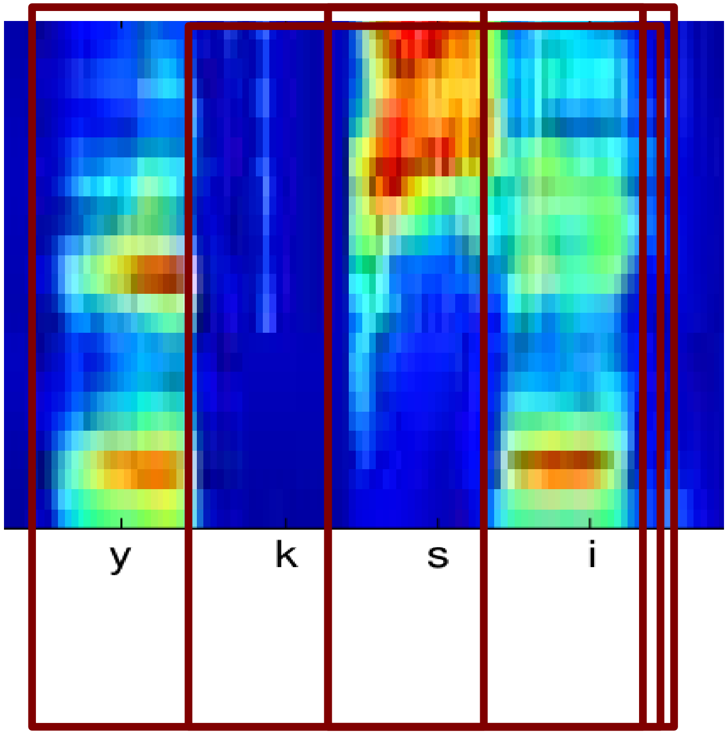
Phone	Example	Phone	Example	Phone	Example
AA	odd	EY	ate	P	pee
AE	at	F	fee	PD	lip
AH	hut	G	green	R	read
AO	ought	GD	bag	S	sea
AW	cow	HH	he	SH	she
AX	abide	IH	it	T	tea
AXR	user	IX	acid	TD	lit
AY	hide	IY	eat	TH	theta
B	be	JH	gee	TS	bits
BD	Dub	K	key	UH	hood
CH	cheese	KD	lick	UW	two
D	dee	L	lee	V	vee
DD	dud	M	me	W	we
DH	thee	N	note	Y	yield
DX	matter	NG	ping	Z	zee
EH	ed	OW	oat	ZH	seizure
ER	hurt	OY	toy	SIL	(silence)

Picture by B.Pellom

Acoustic model of speech

- Discussion: What speech units would suit for ASR?
- (how long, how many, language-dependence)
- (is the linguistic phoneme definition optimal?)





In ASR: Context-dependent phonemes

- **Context independent model,** Monophone /X/
  - Example: three => th + r + iy
  - does a phoneme sound the same in all contexts ?
- **Context dependent model,** Triphone /Left-X+Right/
  - Example: three => sil-**th**+r + th-**r**+iy + r-**iy**+sil
  - 25 phonemes => 25*25*25 = 15 625 triphones
  - do all the contexts exist ?
  - do all the contexts sound different ?
  - can we share parts of the model between some contexts, e.g. beginning, center, middle part?

Content today

1. Preprocessing and features, GMM
2. Phonemes
3. **Hidden Markov Model**
4. Home exercise 2: Build a GMM-HMM system to recognize spoken words

Test what you remember from week 1

Individual test for everyone, now:

1. Go to ***https://kahoot.it*** with your phone/laptop
2. Type in the ID number you see on the screen (also in chat)
3. Give your **REAL (sur)name**
4. Answer the questions by selecting **only one** of the options
   - There may be several right (or wrong) answers, but just pick one
   - About 1 min time per question
5. 1 activity points for everyone + 0.2 per correct answer in time
   - Kahoot score is just for fun, only the correct answers matter

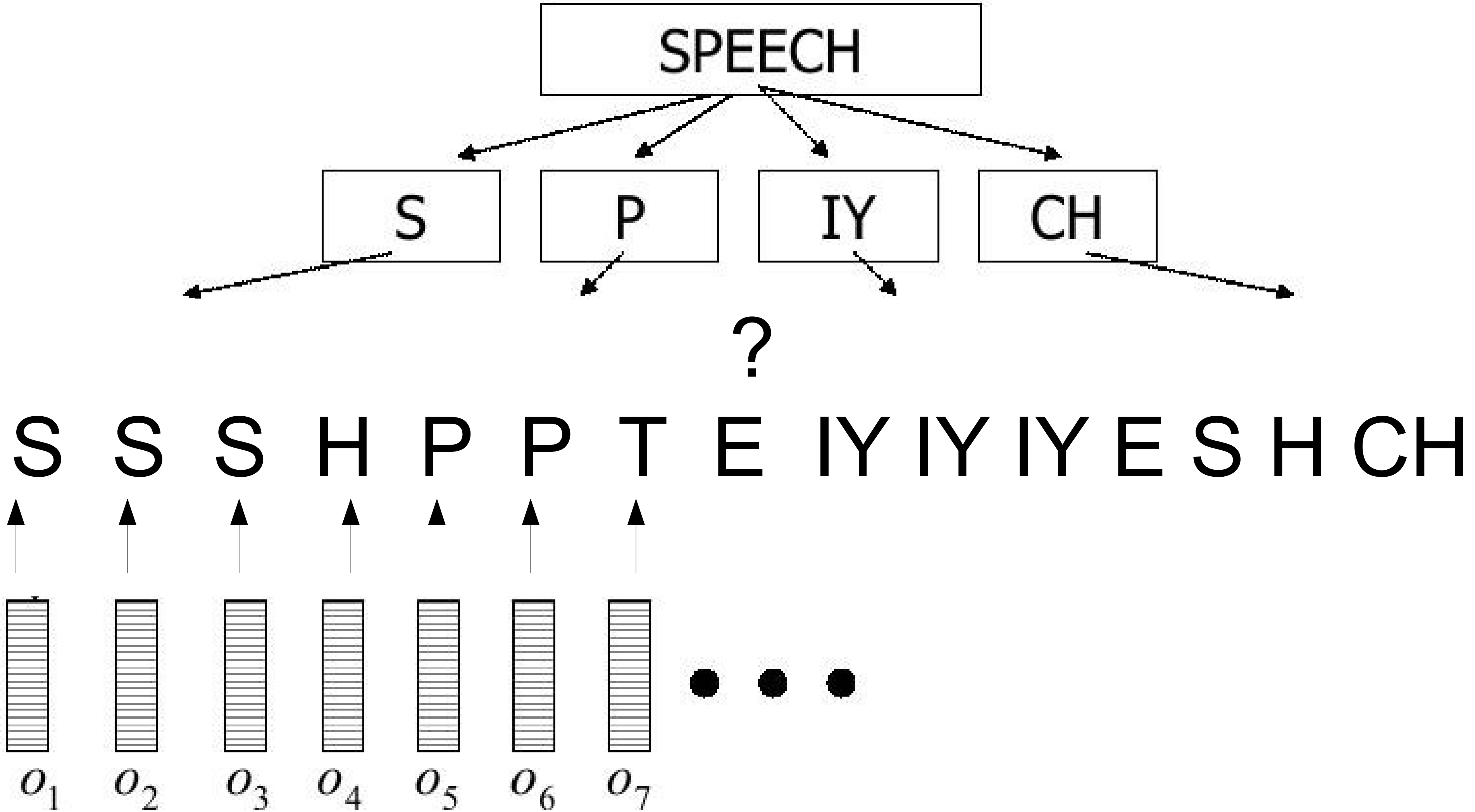
Results of GMM classification?

- This is not yet speech recognition, not even phoneme recognition!
- How to utilize this in phoneme recognition?

ssssssssssssssssssyeeeeeeeeeieeiiiiyiyiiiiiiiiissssssssssssssssssssssstt

ttptpppptkkppkkkkkykooooooooouoooooooooolllllllllllaolmmmmmmmmmmmmmmiiiieeeeyy

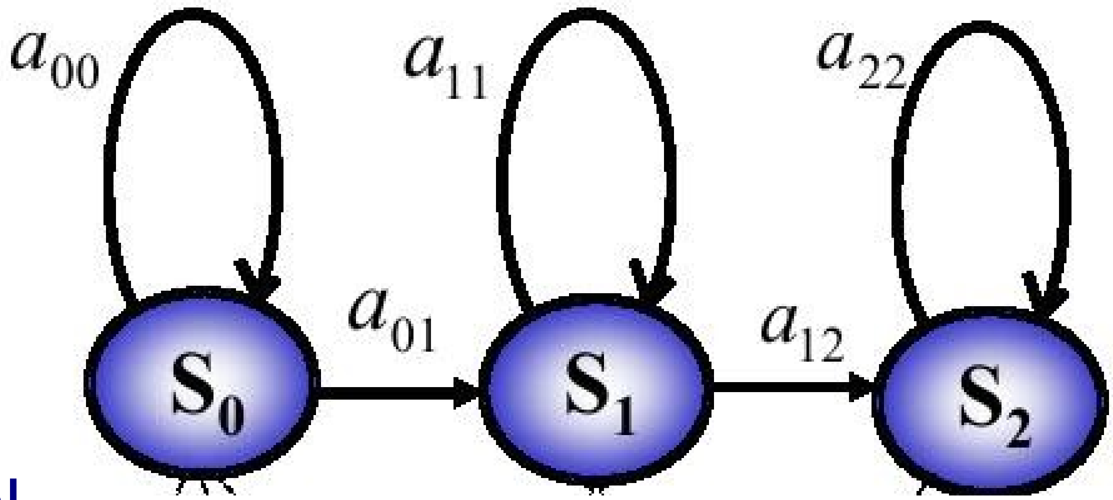
How to model a sequence of frames or phonemes?



Picture by B.Pellom

Hidden Markov model

1. HMM is a system that has a set of operational states
2. From state *i* it moves to state *j* by probability *a(ij)*
3. Each state emits a characteristic sound signal
4. Signals are measured by feature vectors
5. The system's internal **state is hidden**, only the **feature vectors** are **measured**



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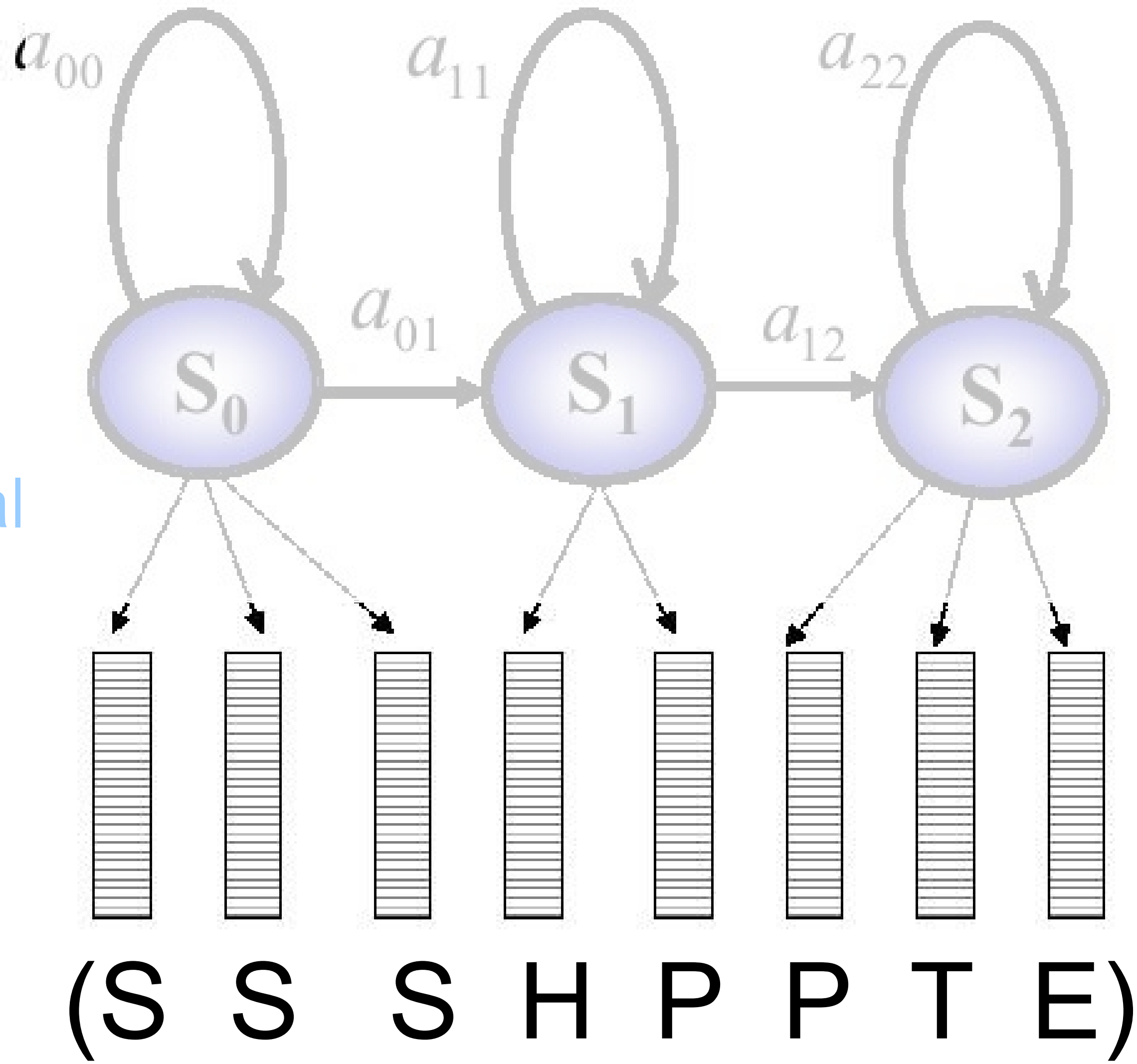

Picture by B.Pellom

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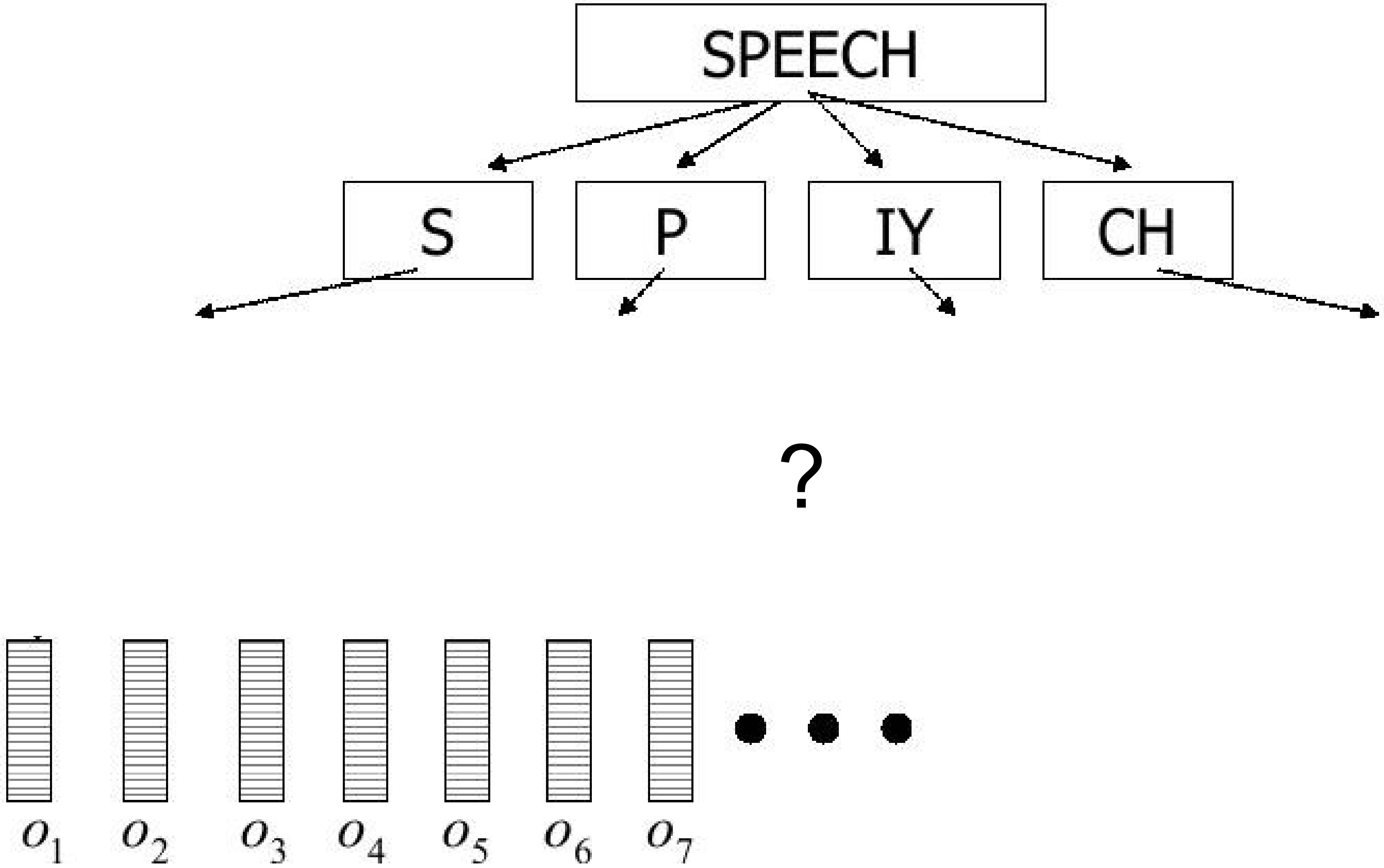
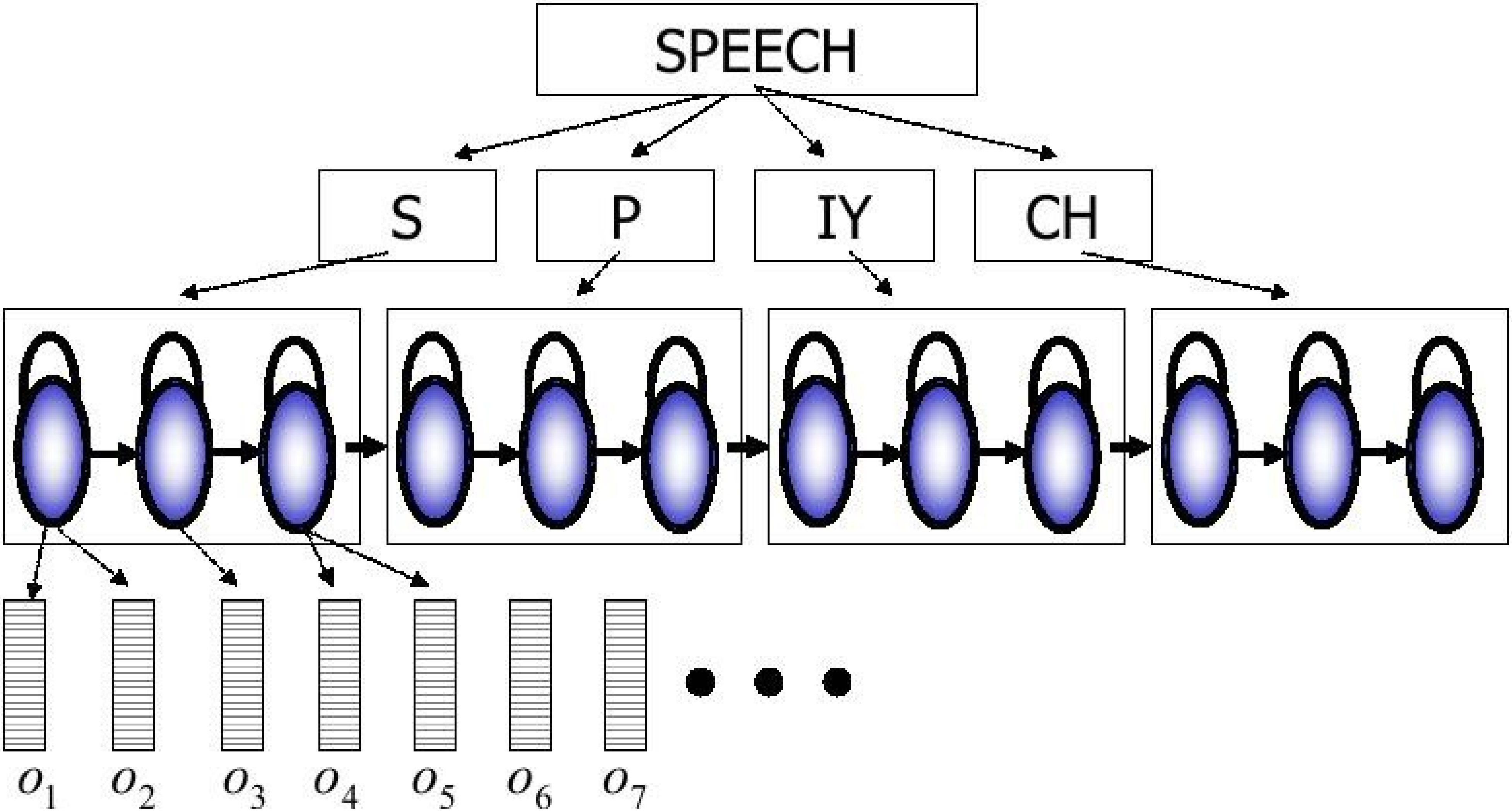


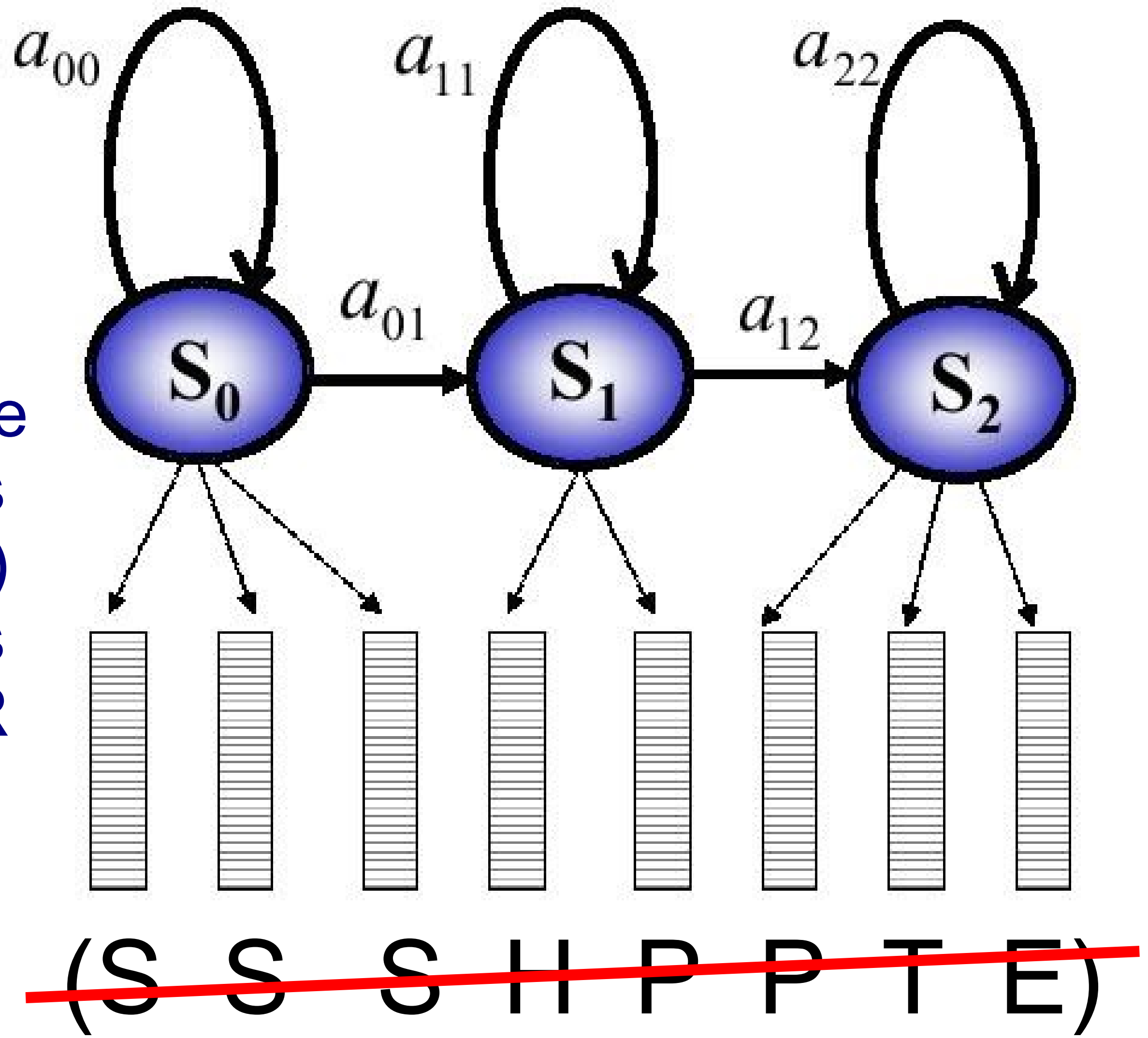
HMM as a phoneme model



(S S S H P P T)

HMM as a phoneme model

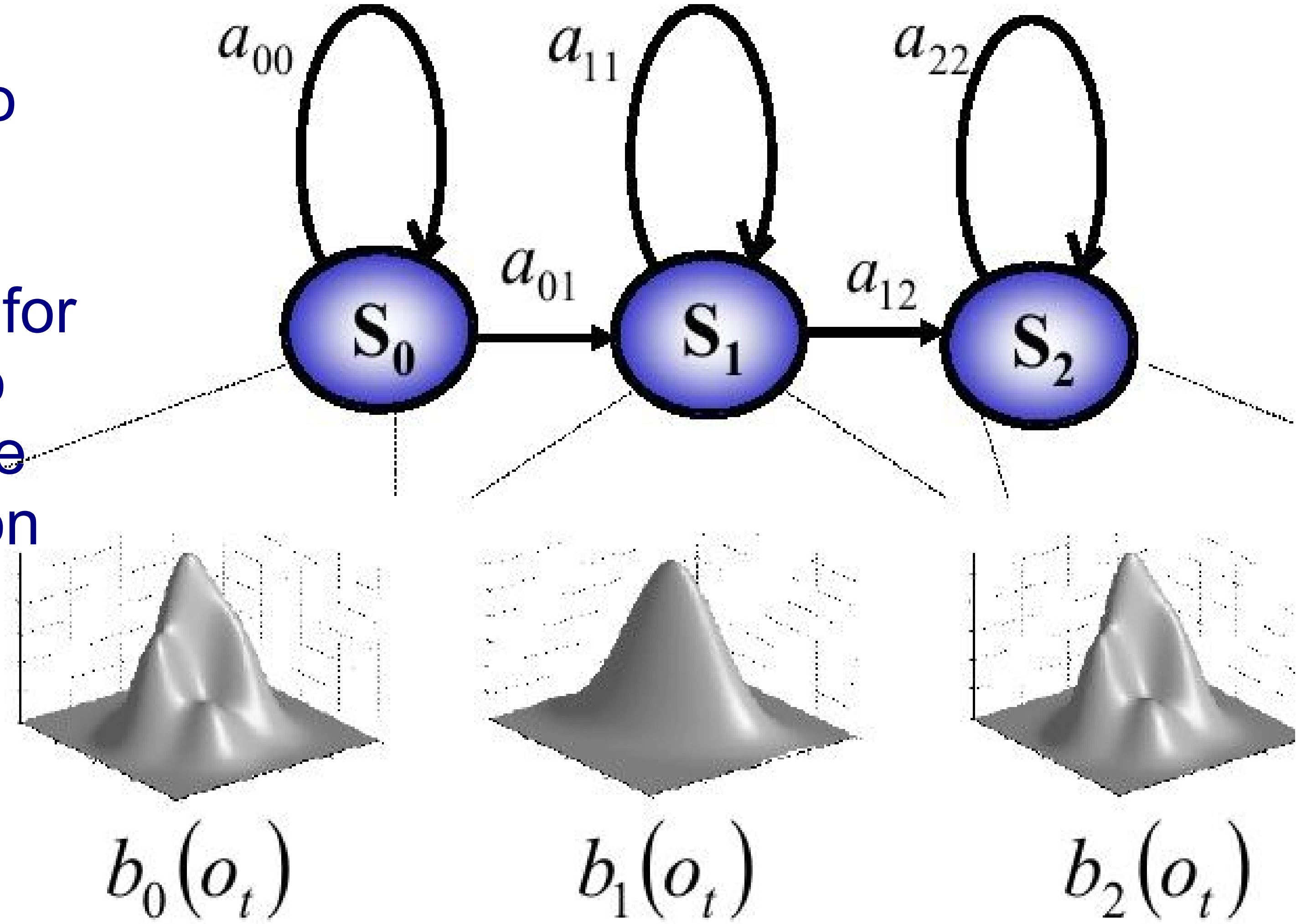
- After **segmenting** each word sample into sounds, we find the set of feature vectors that represent a certain state
- These feature vectors are used to model the outputs in the state (by GMM e.g.)
- After modeling the states the HMM is ready for ASR



Picture by B.Pellom

GMM-HMM system

- Each state emits sounds according to its GMM model
- This generative model can be used for **text-to-speech**, too
- The higher *a(ii)*, the longer is the duration



Picture by B.Pellom

GMM-HMM system

- Each state emits sounds according to its GMM model
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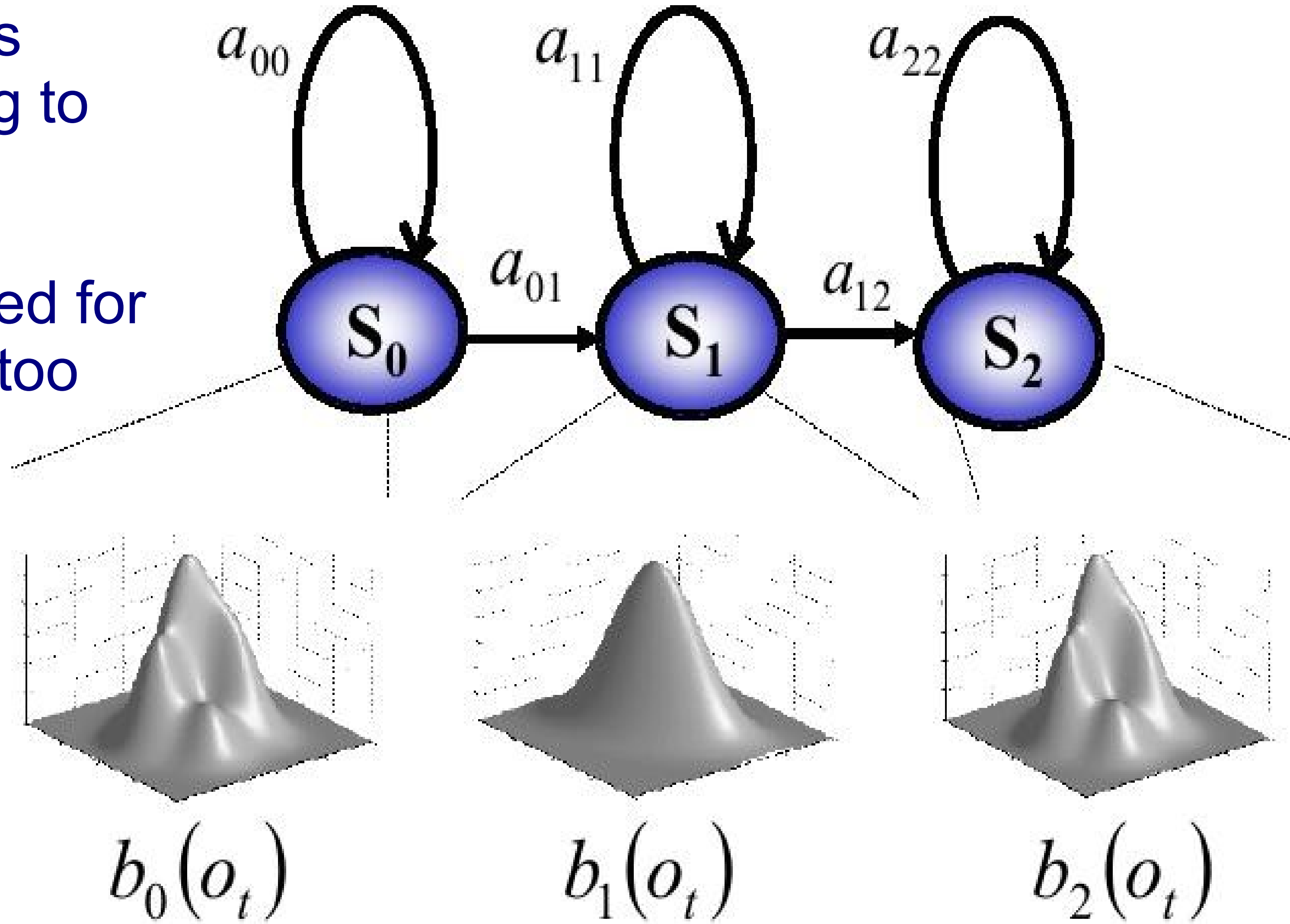
- Sample 1
- Sample 2
- Sample 3



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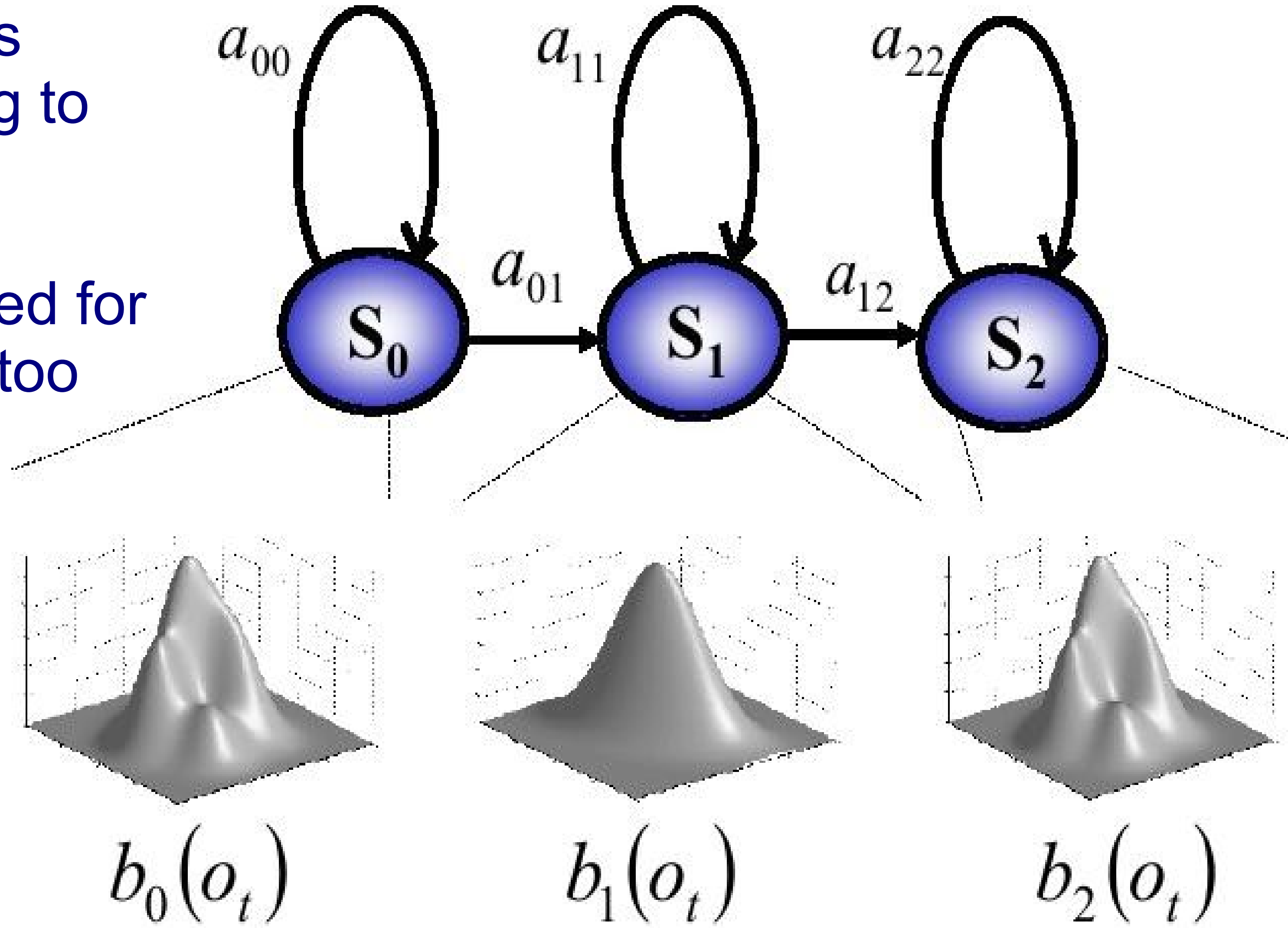

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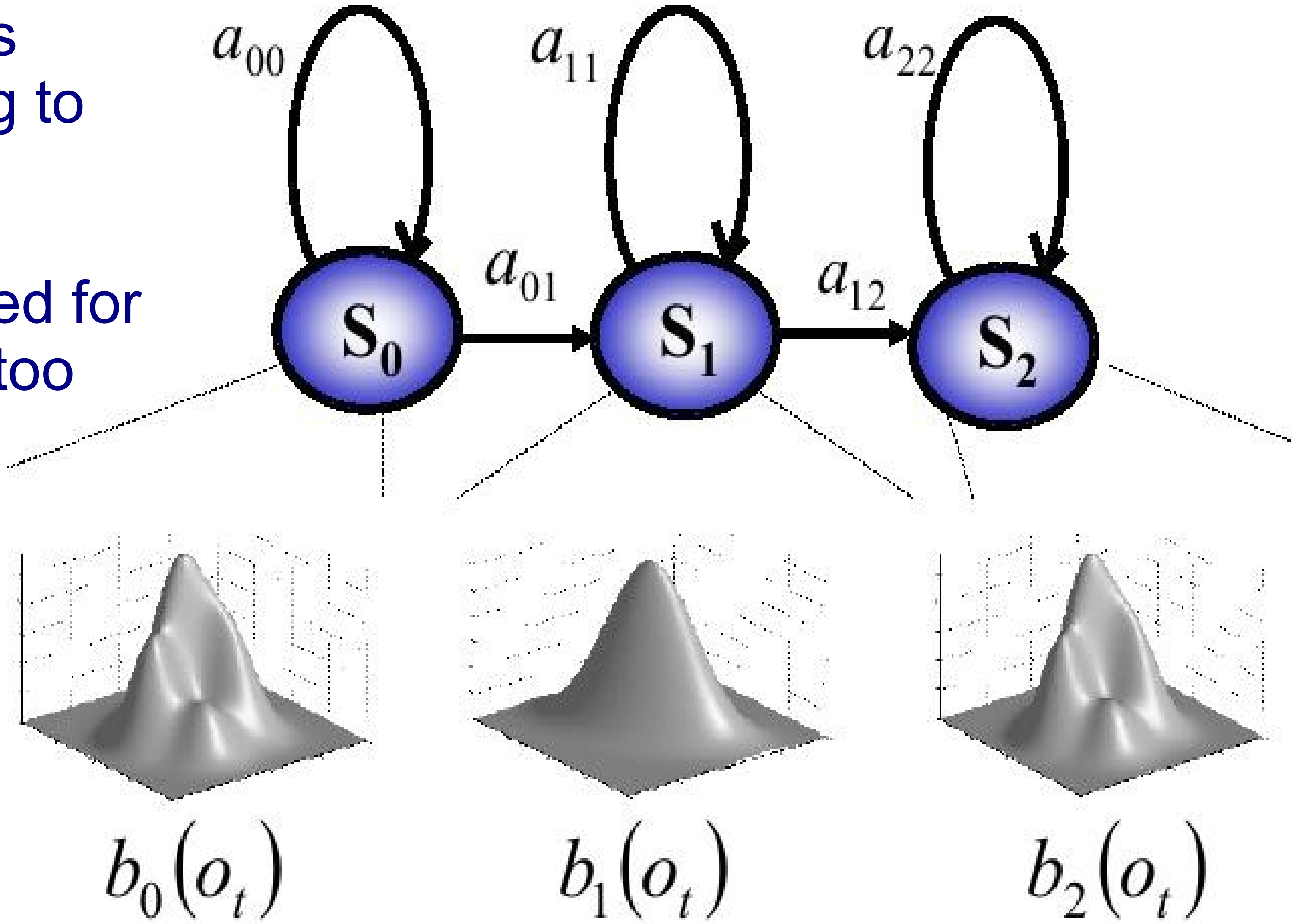


Picture by B.Pellom

Basic operations with HMMs

1. **Scoring**: - How to compute the probability of the observation sequence for a model?

2. **Decoding**: - How to compute the best state sequence for the observations?

3. **Training**: - How to set the model parameters to maximize the probability of the training samples?

GMM-HMM parameters

- Transition probability matrix **a**
  - Transition probability between state i and j is **a**(i,j)
- Observation probability function **b** of feature **x** is **b(x),** for example GMM:

$$f(x) = \sum_{m=1}^{M} w_m \mathrm{N}_m\left(x; \mu_m, \Sigma_m\right)$$

$$= \sum_{m=1}^{M} \frac{w_m}{(2\pi)^{n/2} \left|\Sigma_m\right|^{1/2}} \exp\left[-\frac{1}{2}\left(x - \mu_m\right)^{\mathrm{T}} \Sigma_m^{-1} \left(x - u_m\right)\right]$$

Basic operations with HMMs

1. **Scoring**: - How to compute the probability of the observation sequence for a model?

2. **Decoding**: - How to compute the best state sequence for the observations?

3. **Training**: - How to set the model parameters to maximize the probability of the training samples?

Article: Rabiner (1989), *Tutorial on hidden Markov models and selected applications*

1. Scoring

- Given an observation sequence,

$$\mathbf{O} = \{\mathbf{o}_1, \mathbf{o}_2, \cdots, \mathbf{o}_T\}$$

- Want to compute probability of generating it:

$$P(\mathbf{O} \mid \lambda)$$

- Let's assume a particular sequence of states,

$$q = \{q_1, q_2, \cdots, q_T\}$$

Picture by B.Pellom

Scoring directly

- **Probability of the observation sequence given the state sequence,**

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

$$= b_{q_1}(\mathbf{o}_1) \cdot b_{q_2}(\mathbf{o}_2) \cdots b_{q_T}(\mathbf{o}_T)$$

- **Probability of the state sequence,**

$$P(q \mid \lambda) = \pi_{q_1}(a_{q_1 q_2}) \cdot (a_{q_2 q_3}) \cdots (a_{q_{T-1} q_T})$$

Picture by B.Pellom

Scoring directly?

- **Using the chain rule,**

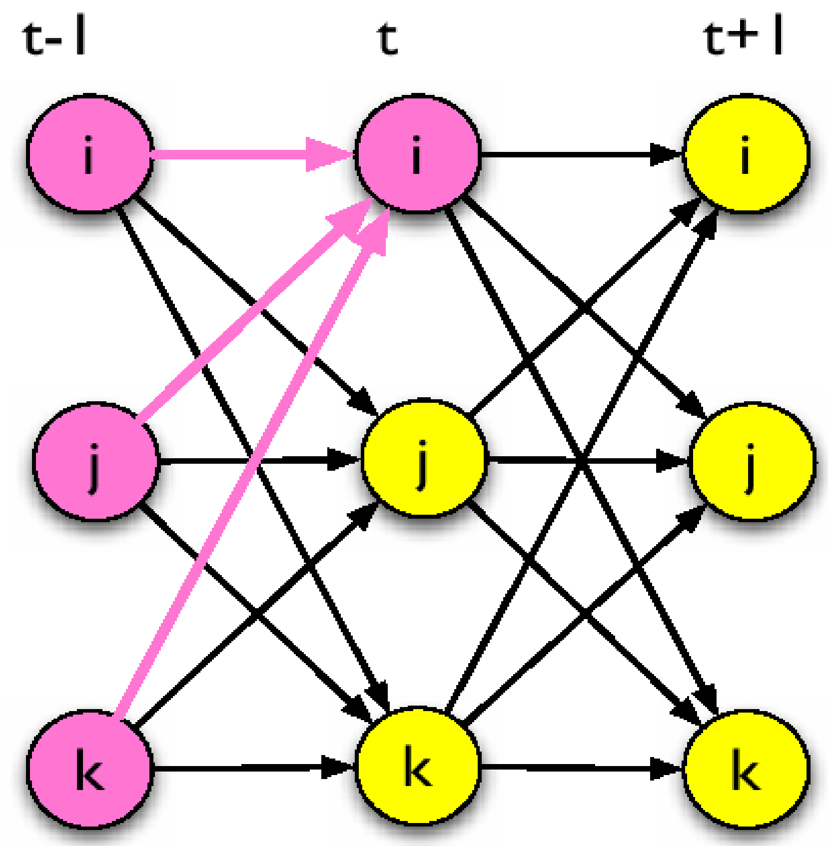
$$\mathrm{P}(\mathbf{O} \mid \lambda) = \sum_{\text{all q}} \mathrm{P}(\mathbf{O} \mid q, \lambda)\mathrm{P}(q \mid \lambda)$$

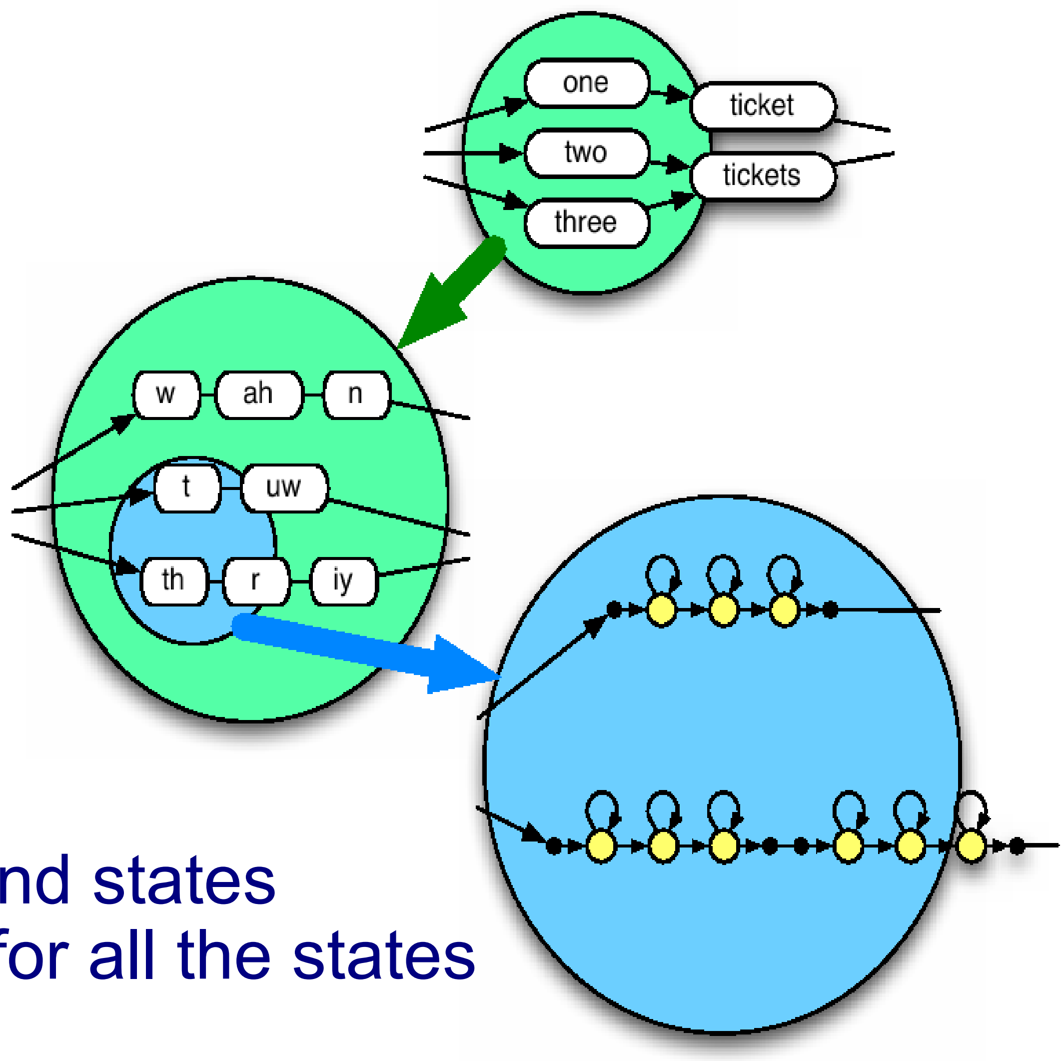
$$= \sum_{\text{all q}} \pi_{q_1} b_{q_1}(\mathrm{o}_1) a_{q_1 q_2} b_{q_2}(\mathrm{o}_2) \cdots a_{q_{T-1} q_T} b_{q_T}(\mathrm{o}_T)$$

- **This is not practical to compute. For N states, T observations, the number of state sequences is:**

$$\mathrm{O}(2T * N^T)$$

Using induction in a search network





1. Map words into phonemes and states
2. Construct a search network for all the states

Picture by S.Renals

Forward algorithm

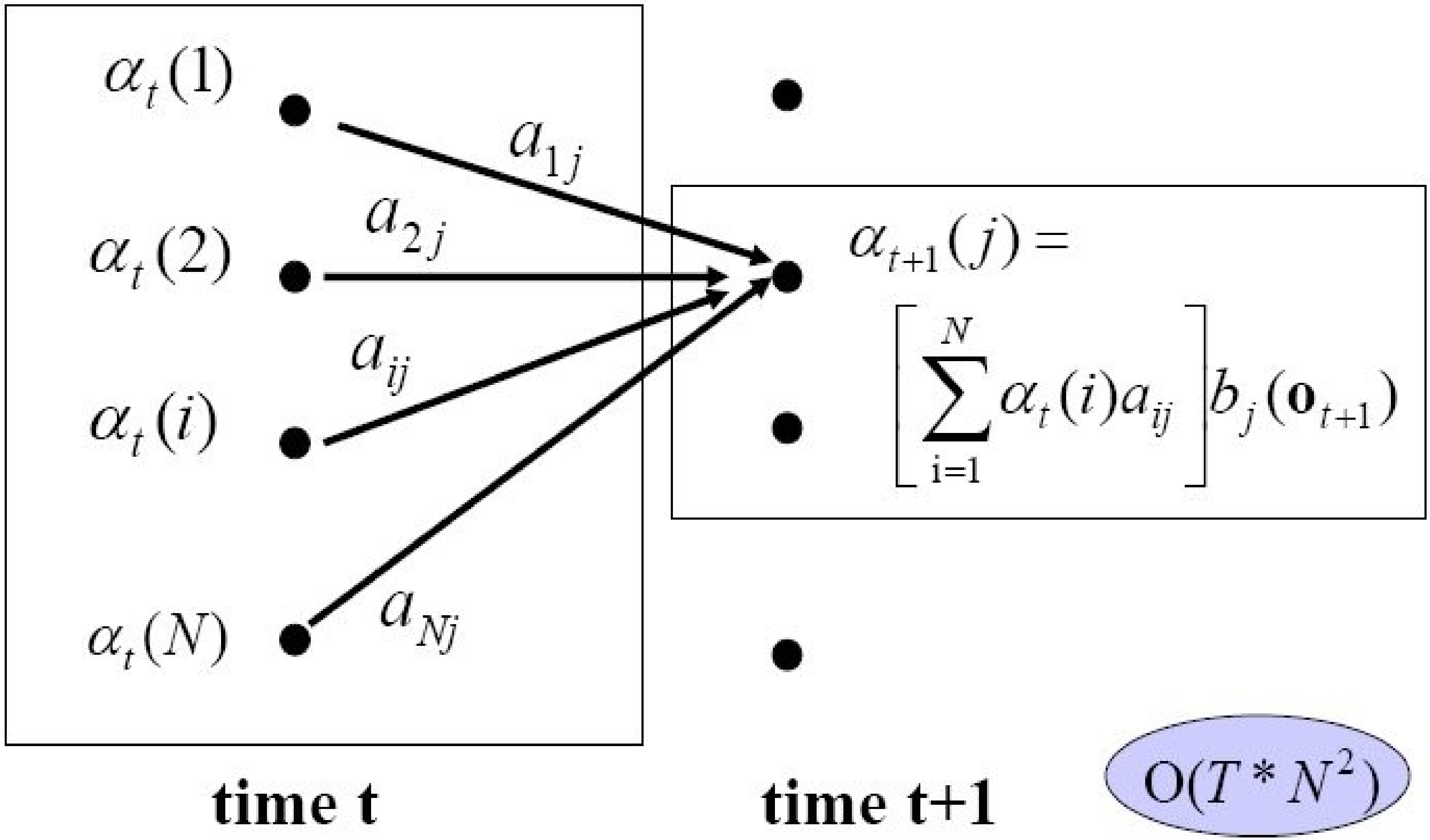
- **Definition:** $\alpha_t(i) = P(\mathbf{o}_1\mathbf{o}_2\ldots\mathbf{o}_t, q_t = i \mid \lambda)$

  (Probability of seeing observations o_1 to o_t and ending at state *i* given HMM λ)

1. **Initialization** $\alpha_0(i) = \pi_i$
2. **Induction** $\alpha_{t+1}(j) = \left[\sum_{i=1}^{N} \alpha_t(i) a_{ij}\right] b_j(\mathbf{o}_{t+1})$
3. **Termination** $P(\mathbf{O} \mid \lambda) = \sum_{i=1}^{N} \alpha_T(i)$

Picture by B.Pellom

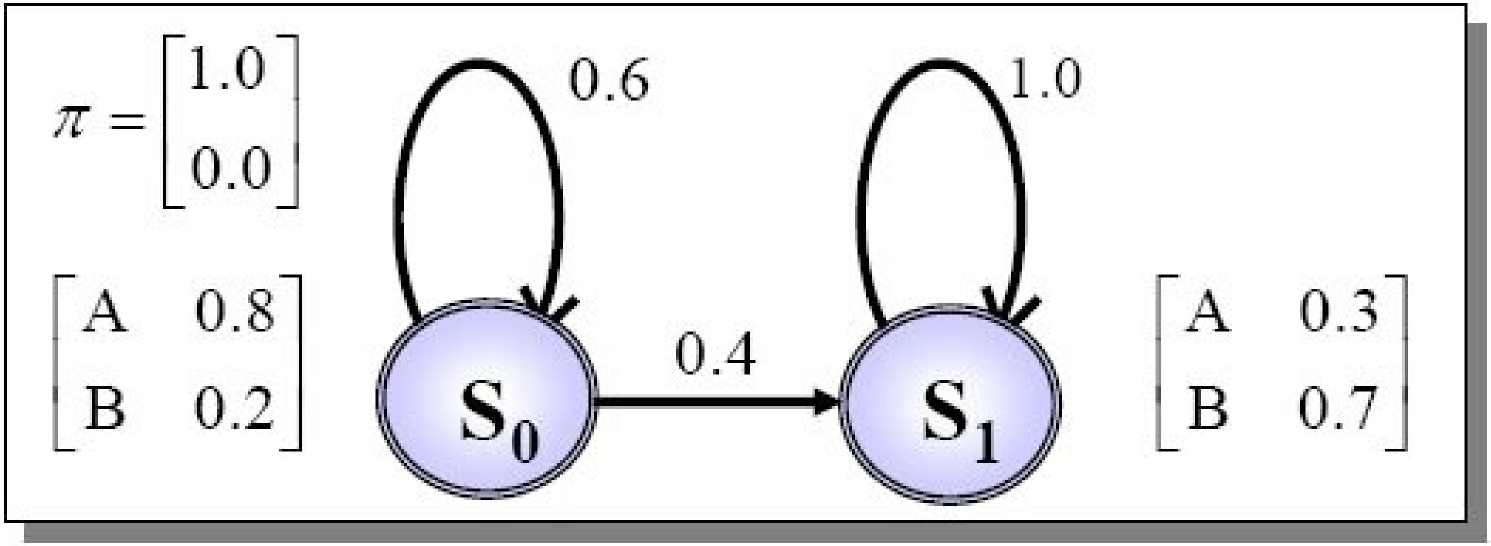
Forward step 2: Induction



$O(T * N^2)$

Picture by B.Pellom

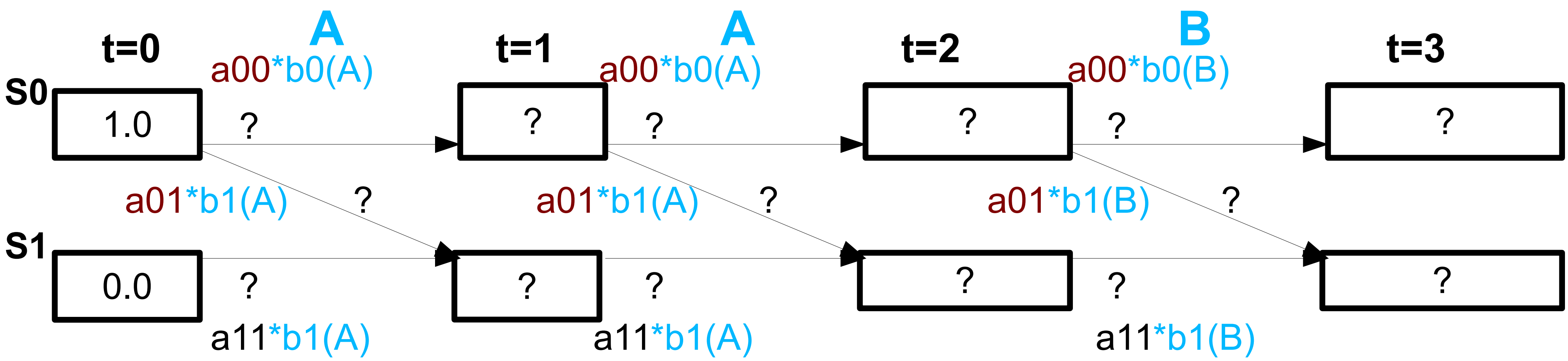
Forward example



- Given the above HMM with discrete observations "A" and "B", what is the probability of generating the sequence "O = {A,A,B}"?
- In other words, find P(O={A,A,B} | λ)

Picture by B.Pellom

Exercise1: Forward algorithm



Answer:

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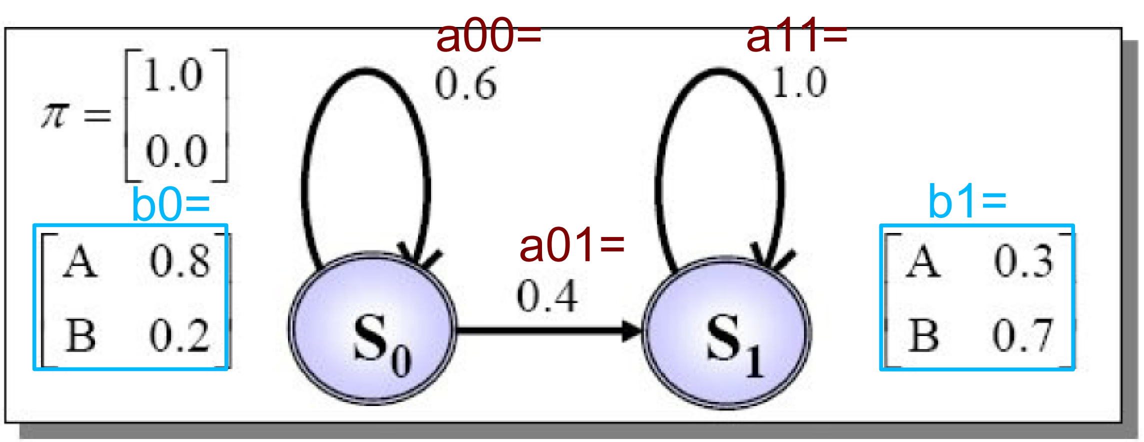

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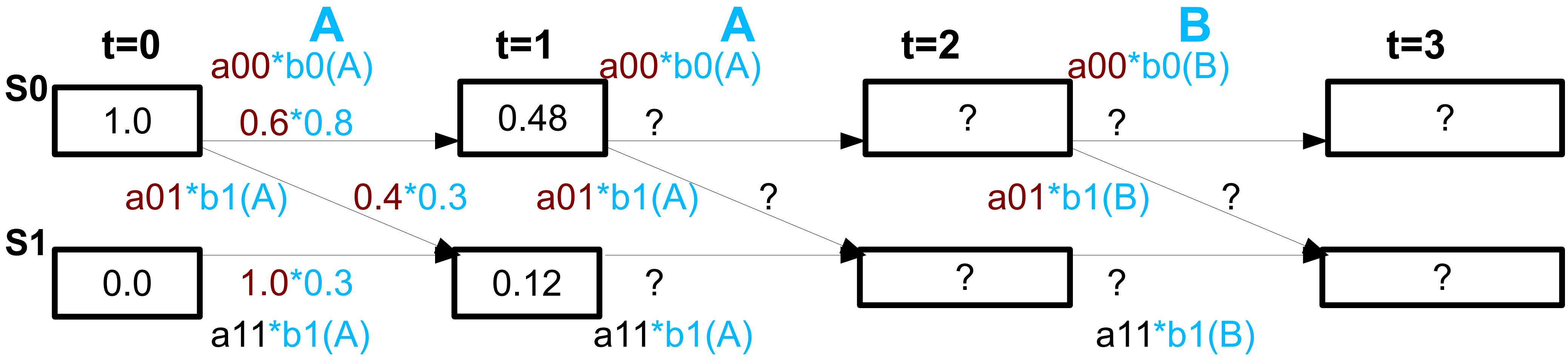

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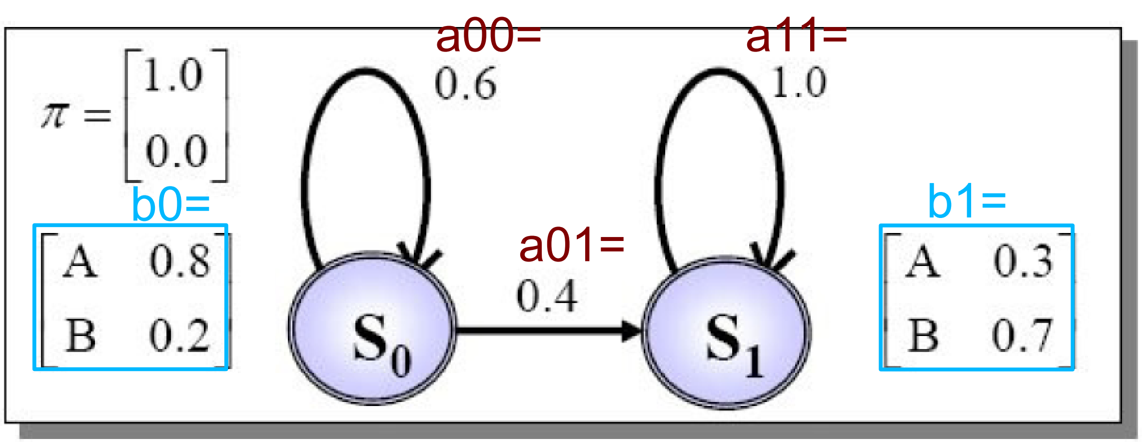

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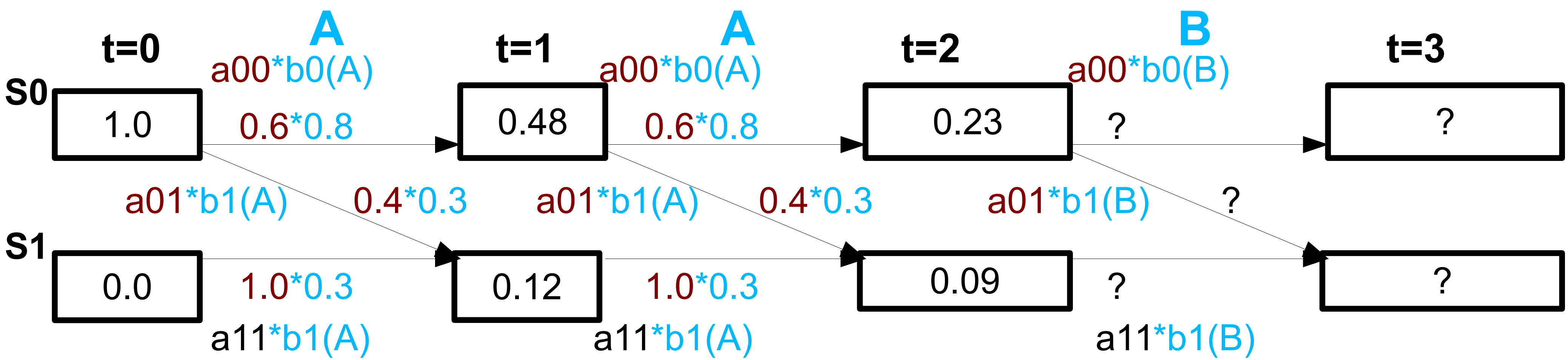

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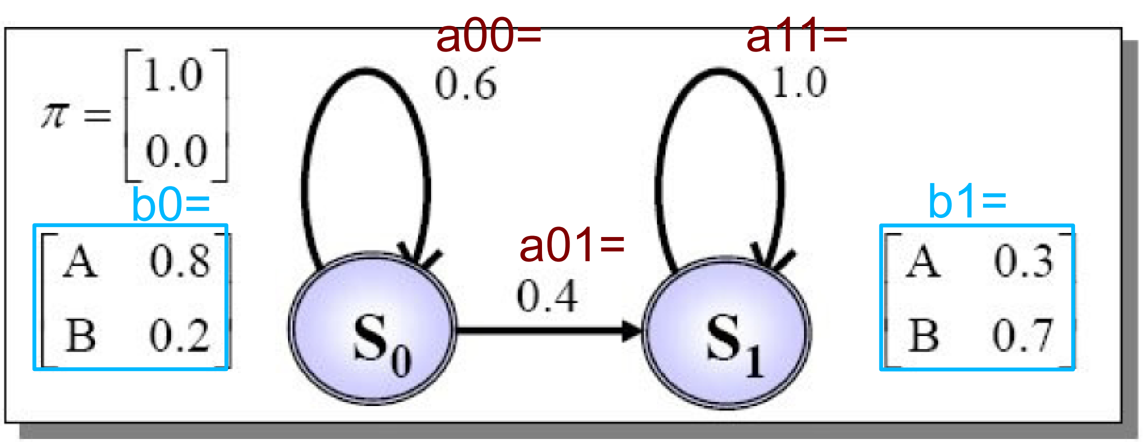

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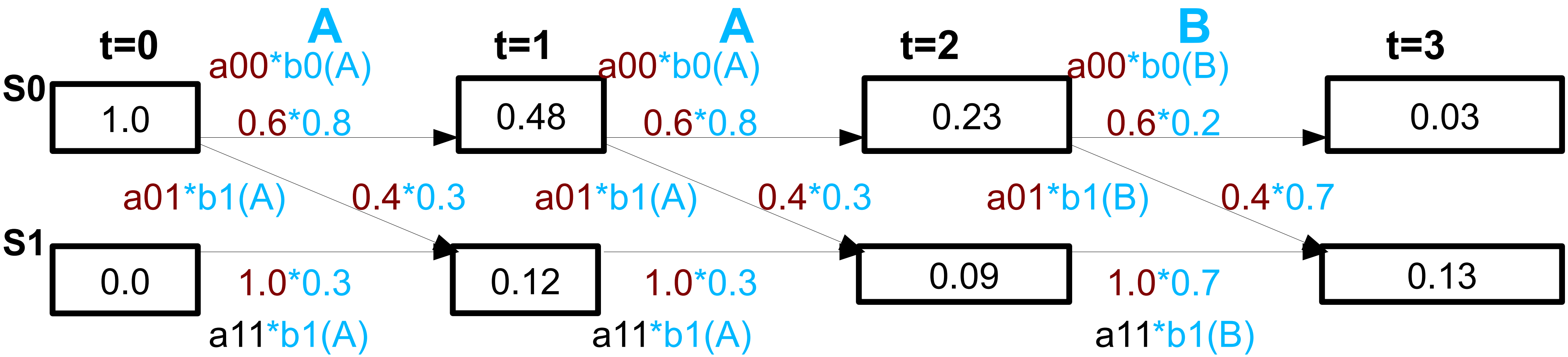

Answer:

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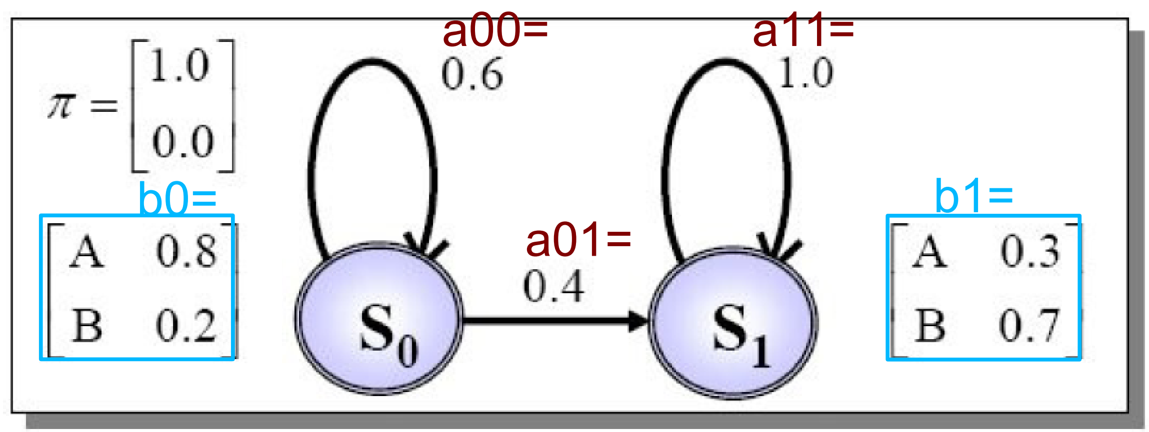

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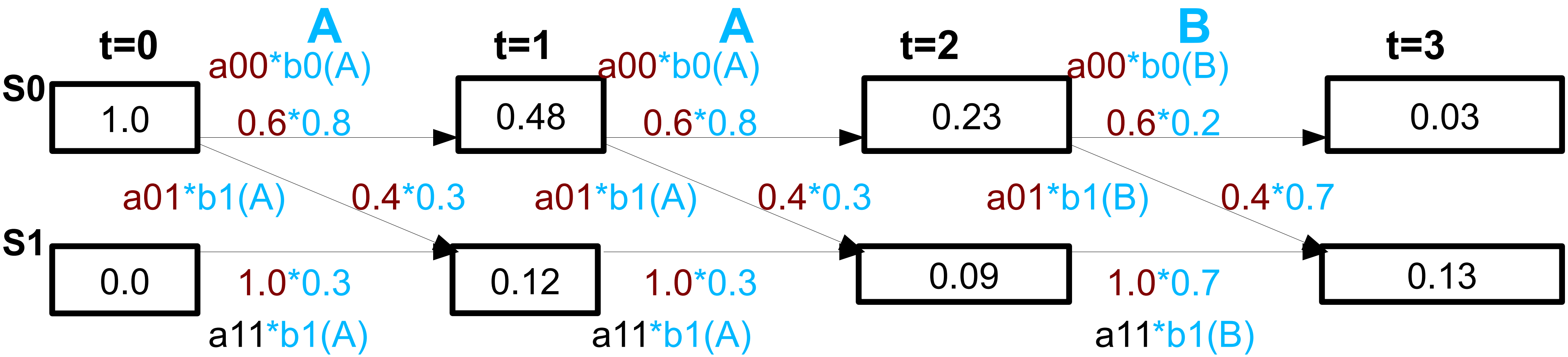
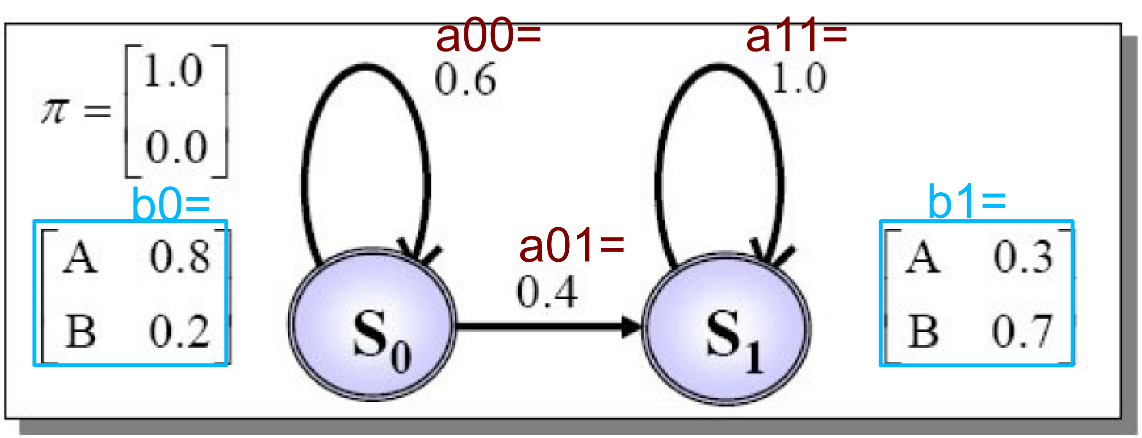


Answer:

P(O|λ)=

0.03+0.13

= 0.16



2. Decoding

- Given an observation sequence,

$$\mathbf{O} = \{\mathbf{o}_1, \mathbf{o}_2, \cdots, \mathbf{o}_T\}$$

- Find the single best sequence of states,

$$q = \{q_1, q_2, \cdots, q_T\}$$

- Which maximizes,

$$P(\mathbf{O}, q \mid \lambda)$$

Viterbi algorithm

1. Initialization $\delta_1(i) = \pi_i b_i(\mathbf{o}_1) \quad \psi_1(i) = 0$

2. Recursion

$$\delta_t(j) = \max_{1\le i\le N}[\delta_{t-1}(i)a_{ij}]b_j(\mathbf{o}_t)$$

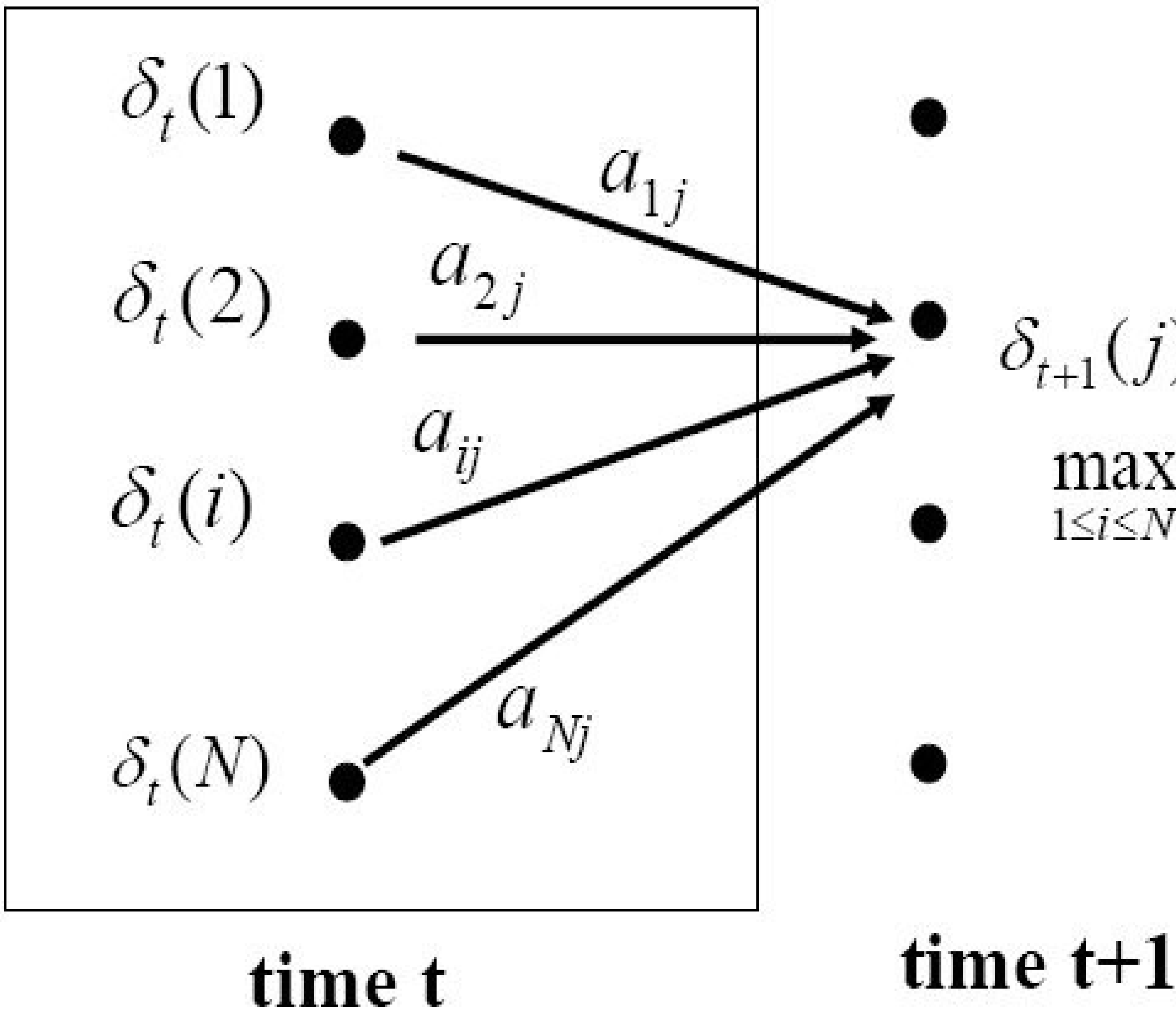
$$\psi_t(j) = \arg\max_{1\le i\le N}[\delta_{t-1}(i)a_{ij}]$$

3. Termination $P^* = \max_{1\le i\le N}\left[\delta_T(i)\right] \quad q_T^* = \arg\max_{1\le i\le N}\left[\delta_T(i)\right]$

4. Path Back trace $q_t^* = \psi_{t+1}(q_{t+1}^*)$

Picture by B.Pellom

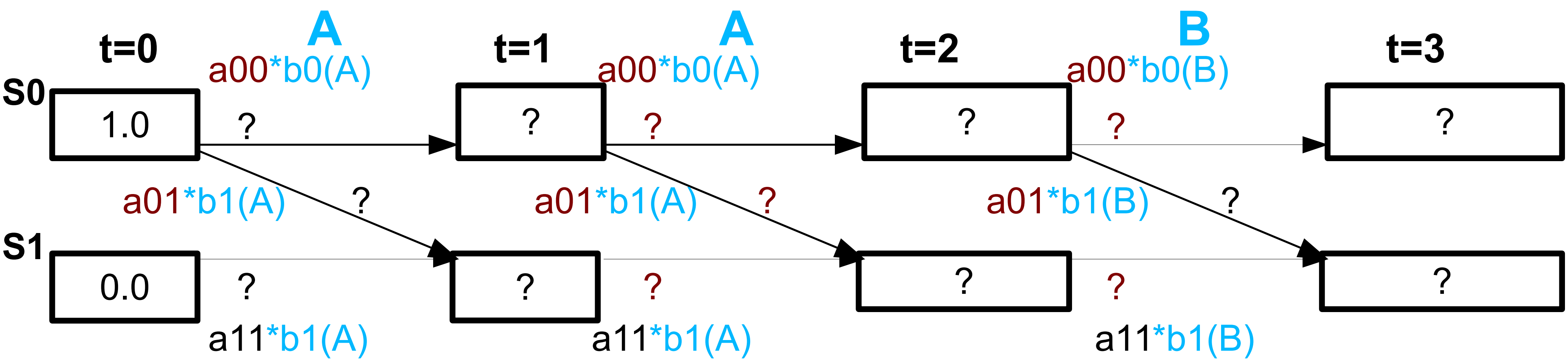
Viterbi step 2: Recursion



$$\delta_{t+1}(j) = \max_{1 \le i \le N} [\delta_t(i) a_{ij}] b_j(\mathbf{o}_{t+1})$$

Picture by B.Pellom

Exercise2: Viterbi search



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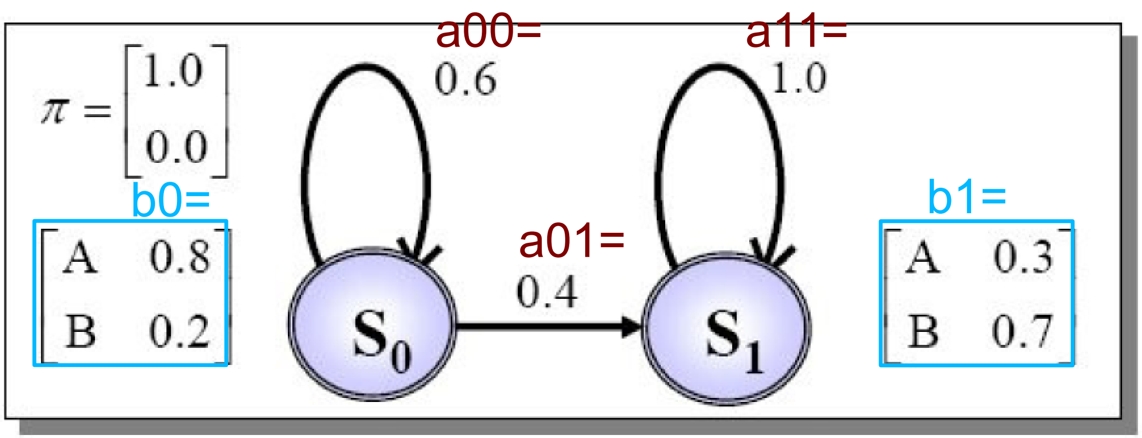

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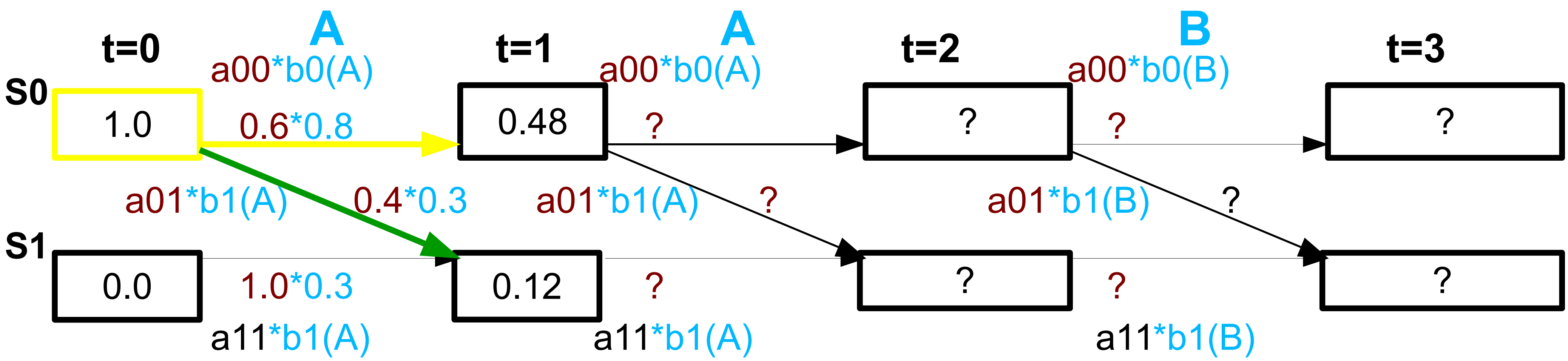

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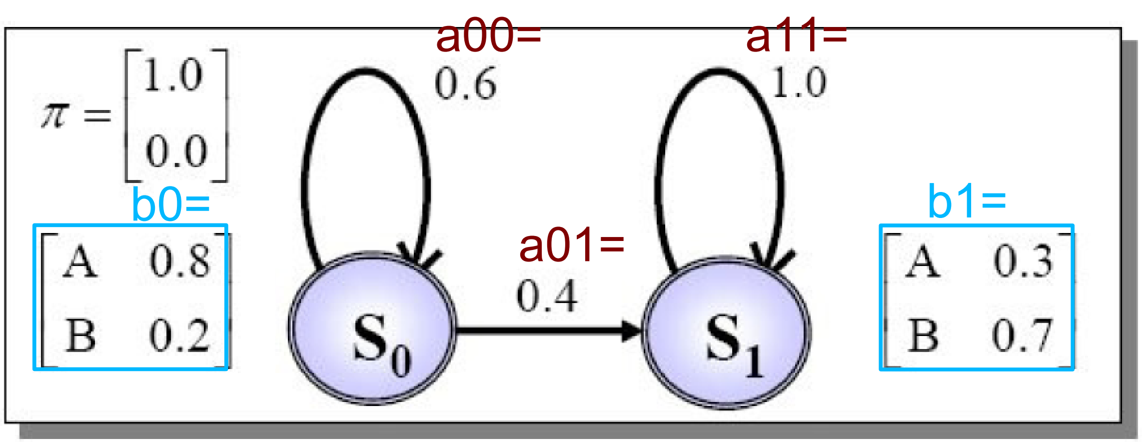

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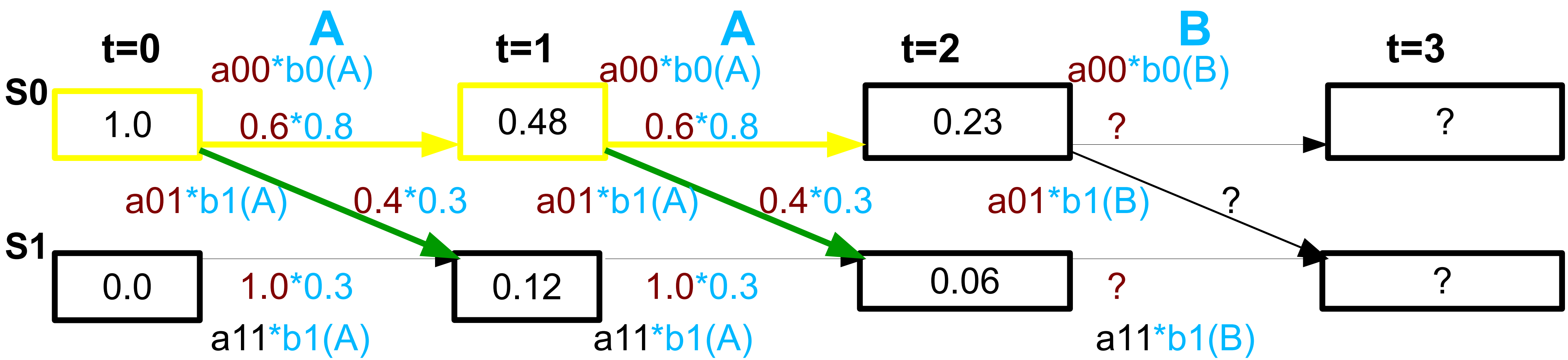

Answer:

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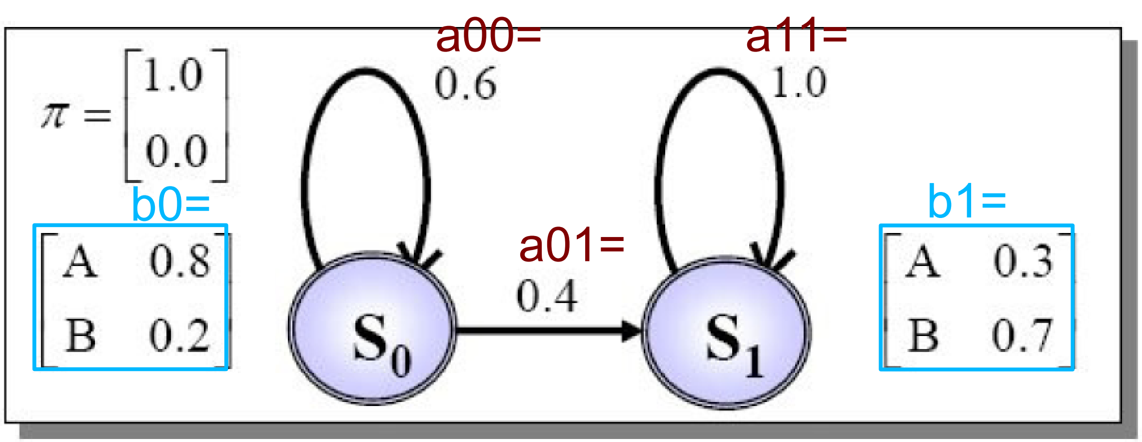

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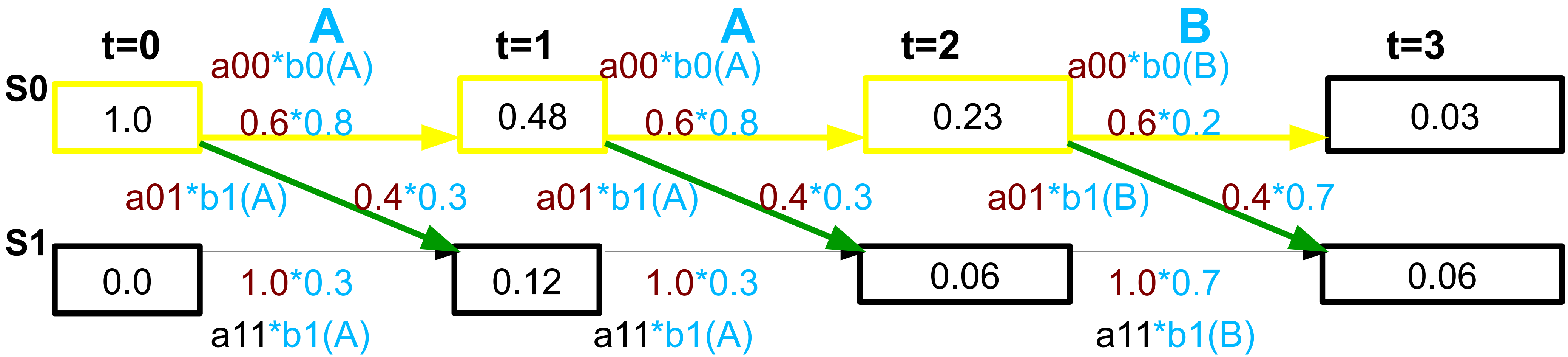

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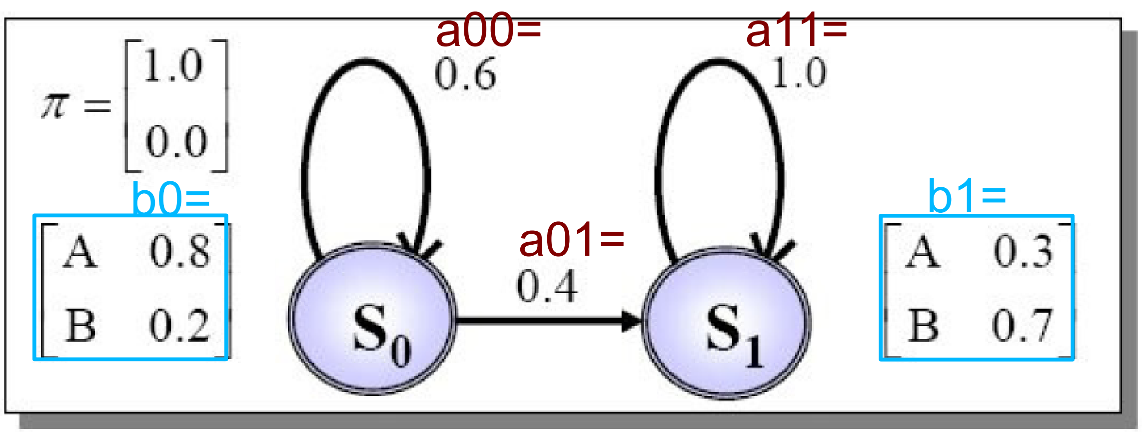
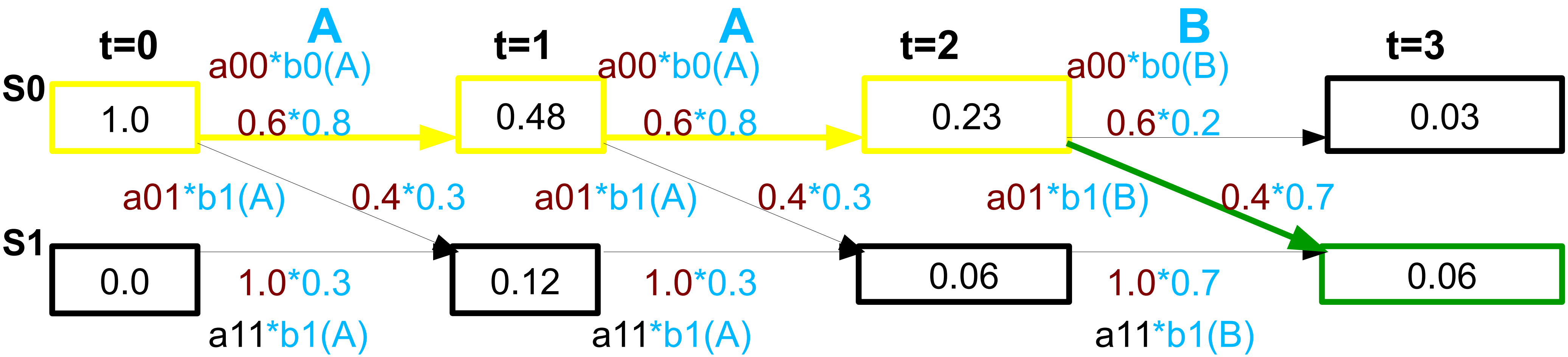
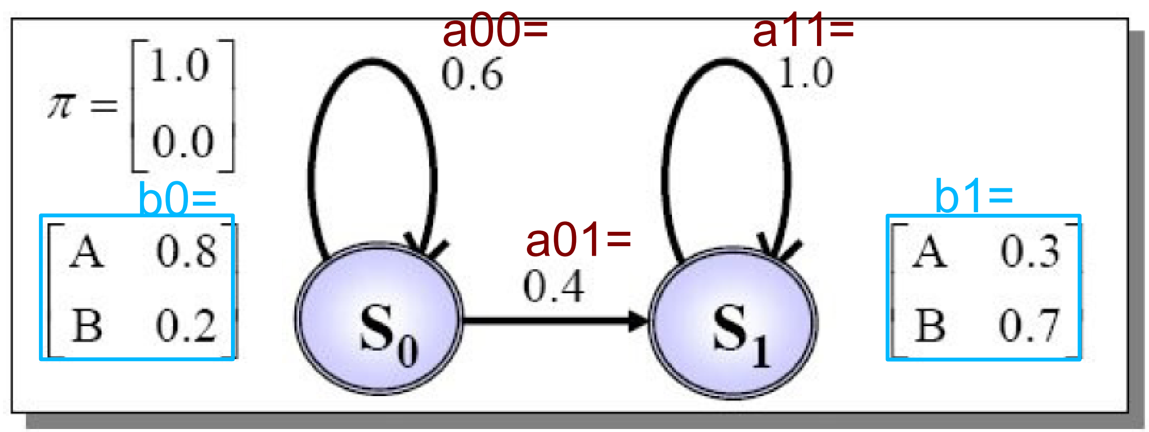


Exercise2: Viterbi search



Answer:

S0-S0-S1



3. Training

- **Forward-Backward** algorithm (a.k.a. Baum-Welch):
  - 1. Initialize the model parameters *(a,b)*
  - 2. Use the model and Forward (or Backward) algorithm to compute the probability matrix ***P(state=i,time=t |a,b)*** **for each sample**
  - 3. Use *P* to **enhance the model** parameters:
    - *a(ij)* : expected number of transitions from *i* to *j*
    - *b_i(o)* : expected pdf of features in state *i* (weighted by P)
  - 4. **Iterate** from 2.

Viterbi training

- Like Forward-Backward algorithm, but substitutes the **sum** operation by **max**
- Instead of summing probabilities over all HMM paths, **only use the best path** for each sample
- Like Viterbi decoding, but only the best **alignment** (segmentation) between the speech and text needed
- Simpler than F-B, but converges likewise to the (local) optimum
- *"Hard alignment"* in V, but *"soft alignment"* in F-B

Context-dependent HMM

- **Monophone** HMM = context-independent phoneme
  - three => th + r + iy
- **Triphone** HMM = context-dependent phonemes
  - three => sil-**th**+r + th-**r**+iy + r-**iy**+sil
- Difficult decisions needed in HMM design:
  - How many models, states and Gaussians?
  - Share models between some triphones?
  - Share states or Gaussians between models?

HMM assumptions

1. The HMM **topology** is usually fixed, e.g. left-to-right
2. The state **duration** is exponentially distributed
3. The **transition** between states is independent of time and state history: - It only depends on the current state
4. The **observations** are independent of time and each other: - They only depend on the current state

Feedback

Now: Go to **MyCourses > Lectures** and fill in the feedback form.

Some of the feedback from the previous week:

+ interactive and interesting lecture

+ kahoot, audio samples and example calculations

- more details on features

- kahoot took too much time

If possible, the microphone of the lecturer could be better.

I would like to choose my own project topic!

Thanks for all the valuable feedback!

Summary of today

- Phonemes
- GMM and HMM
- **Next meeting:** Thu 10.15 – 12 or Fri 14.15 – 16: Speech recognition by HTK toolkit
  - check *http://htk.eng.cam.ac.uk/docs/docs.shtml*
  - This exercises is useful for most project works!
- **Next week:** Language models and lexicon

Project work receipt

1. Form a group (3 persons)
2. Get a topic
3. Get reading material from M*ycourses* or your group tutor
4. 1st meeting: Specify the topic, start literature study (DL Nov 8)
5. **2nd meeting: Write a work plan (DL Nov 11)** — **This week**
6. 3rd - 5th meetings: Perform analysis, experiments, and write a report
7. Book your presentation time for weeks 6 - 7 (DL Nov 27)
8. Prepare and keep your 20 min presentation
9. Return the report (DL Dec 11)

Check **MyCourses > Projects** to see your group, topic and tutor

Final project report

1. Abstract: (your working plan)
2. Introduction: (your literature review)
   - Remember to cite every article you read
3. Experiments: Describe what you did
4. Results: Describe the results you got
5. Conclusion: Your conclusion of the work
6. References: (list of articles that you read)