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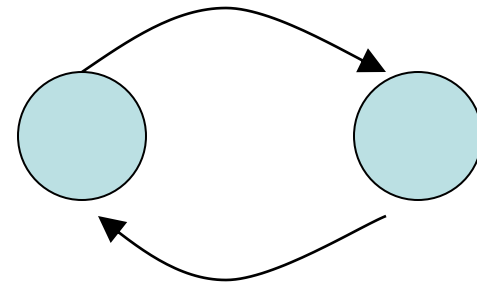
Machine Learning

Hidden Markov models (HMMs)

What's wrong with Bayesian networks

- Bayesian networks are very useful for modeling joint distributions
- But they have their limitations:
 - Cannot account for temporal / sequence models
 - DAG's (no self or any other loops)

**This is not a valid
Bayesian network!**



Hidden Markov models

- Model a set of observation with a set of hidden states
 - Robot movement

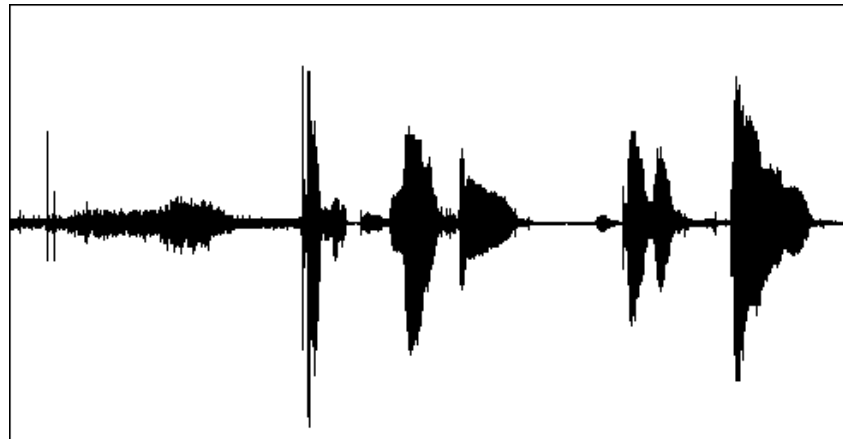
Observations: range sensor, visual sensor

Hidden states: location (on a map)



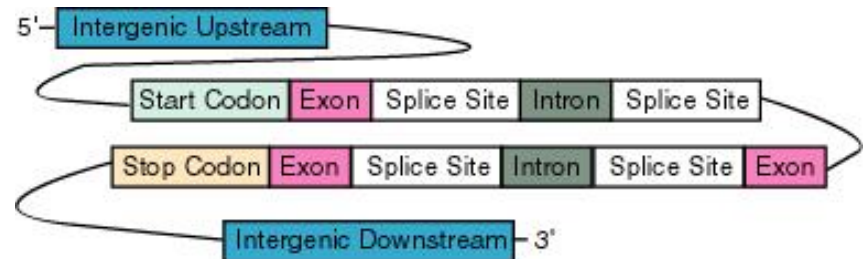
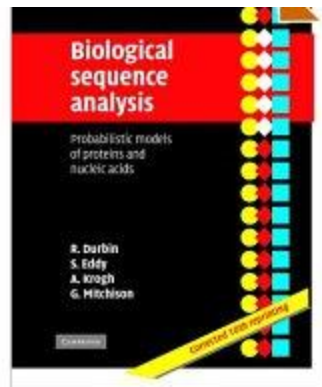
1. Hidden states generate observations
2. Hidden states transition to other hidden states

Examples: Speech processing



sil	acht	negen	sil	drie	een
sil	spk	spk	sil	spk	spk

Example: Biological data



ATGAAGCTACTGTCTTCTATCGAACAAGCATGCG
ATATTTGCCGACTTAAAAAGCTCAAG
TGCTCCAAAGAAAAACCGAAGTGCGCCAAGTGT
CTGAAGAACAACCTGGGAGTGTCGCTAC
TCTCCCAAACCAAAAGGTCTCCGCTGACTAGG
GCACATCTGACAGAAGTGGAATCAAGG
CTAGAAAGACTGGAACAGCTATTTCTACTGATTTT
TCCTCGAGAAGACCTTGACATGATT

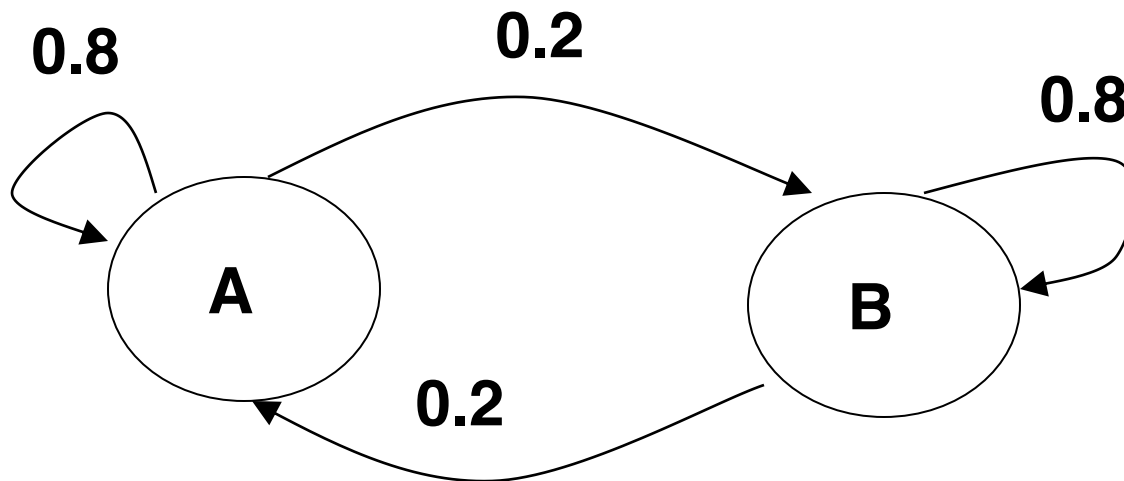
Contents

<i>Preface</i>	<i>page ix</i>
1 Introduction	1
1.1 Sequence similarity, homology, and alignment	2
1.2 Overview of the book	2
1.3 Probabilities and probabilistic models	4
1.4 Further reading	10
2 Pairwise alignment	12
2.1 Introduction	12
2.2 The scoring model	13
2.3 Alignment algorithms	17
2.4 Dynamic programming with more complex models	28
2.5 Heuristic alignment algorithms	32
2.6 Linear space alignments	34
2.7 Significance of scores	36
2.8 Deriving score parameters from alignment data	41
2.9 Further reading	45
3 Markov chains and hidden Markov models	46
3.1 Markov chains	48
3.2 Hidden Markov models	51
3.3 Parameter estimation for HMMs	62
3.4 HMM model structure	68
3.5 More complex Markov chains	72
3.6 Numerical stability of HMM algorithms	77
3.7 Further reading	79
4 Pairwise alignment using HMMs	80
4.1 Pair HMMs	81
4.2 The full probability of x and y , summing over all paths	87
4.3 Suboptimal alignment	89
4.4 The posterior probability that x_i is aligned to y_j	91
4.5 Pair HMMs versus FSAs for searching	95

4.6	<i>Further reading</i>	98
5	Profile HMMs for sequence families	100
5.1	<i>Ungapped score matrices</i>	102
5.2	<i>Adding insert and delete states to obtain profile HMMs</i>	102
5.3	<i>Deriving profile HMMs from multiple alignments</i>	105
5.4	<i>Searching with profile HMMs</i>	108
5.5	<i>Profile HMM variants for non-global alignments</i>	113
5.6	<i>More on estimation of probabilities</i>	115
5.7	<i>Optimal model construction</i>	122
5.8	<i>Weighting training sequences</i>	124
5.9	<i>Further reading</i>	132
6	Multiple sequence alignment methods	134
6.1	<i>What a multiple alignment means</i>	135
6.2	<i>Scoring a multiple alignment</i>	137
6.3	<i>Multidimensional dynamic programming</i>	141
6.4	<i>Progressive alignment methods</i>	143
6.5	<i>Multiple alignment by profile HMM training</i>	149
6.6	<i>Further reading</i>	159
7	Building phylogenetic trees	160
7.1	<i>The tree of life</i>	160
7.2	<i>Background on trees</i>	161
7.3	<i>Making a tree from pairwise distances</i>	165
7.4	<i>Parsimony</i>	173
7.5	<i>Assessing the trees: the bootstrap</i>	179
7.6	<i>Simultaneous alignment and phylogeny</i>	180
7.7	<i>Further reading</i>	188
7.8	<i>Appendix: proof of neighbour-joining theorem</i>	190
8	Probabilistic approaches to phylogeny	192
8.1	<i>Introduction</i>	192
8.2	<i>Probabilistic models of evolution</i>	193
8.3	<i>Calculating the likelihood for ungapped alignments</i>	197
8.4	<i>Using the likelihood for inference</i>	205
8.5	<i>Towards more realistic evolutionary models</i>	215
8.6	<i>Comparison of probabilistic and non-probabilistic methods</i>	224
8.7	<i>Further reading</i>	231

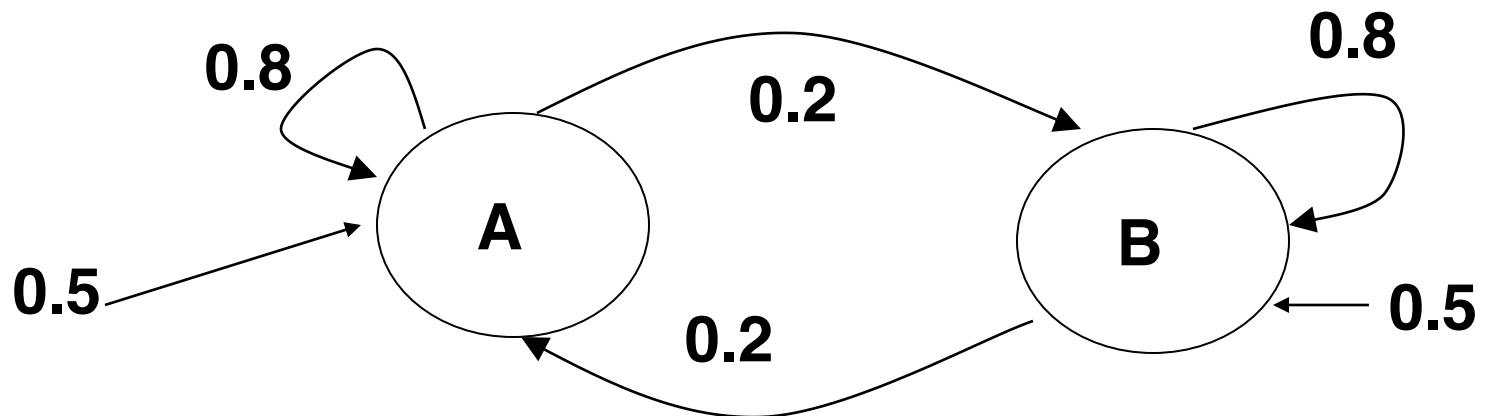
Example: Gambling on dice outcome

- Two dices, both skewed (output model).
- Can either stay with the same dice or switch to the second dice (transition mode).



A Hidden Markov model

- A set of states $\{s_1 \dots s_n\}$
 - In each time point we are in exactly one of these states denoted by q_t
- Π_i , the probability that we *start* at state s_i
- A transition probability model, $P(q_t = s_i \mid q_{t-1} = s_j)$
- A set of possible outputs Σ
 - At time t we emit a symbol $\sigma \in \Sigma$
- An emission probability model, $p(o_t = \sigma \mid s_i)$



The Markov property

- A set of states $\{s_1 \dots s_n\}$
 - In each time point we are in exactly one of these states denoted by q_t
- Π_i , the probability that we start at state s_i
- A transition probability model, $P(q_t = s_i \mid q_{t-1} = s_j)$

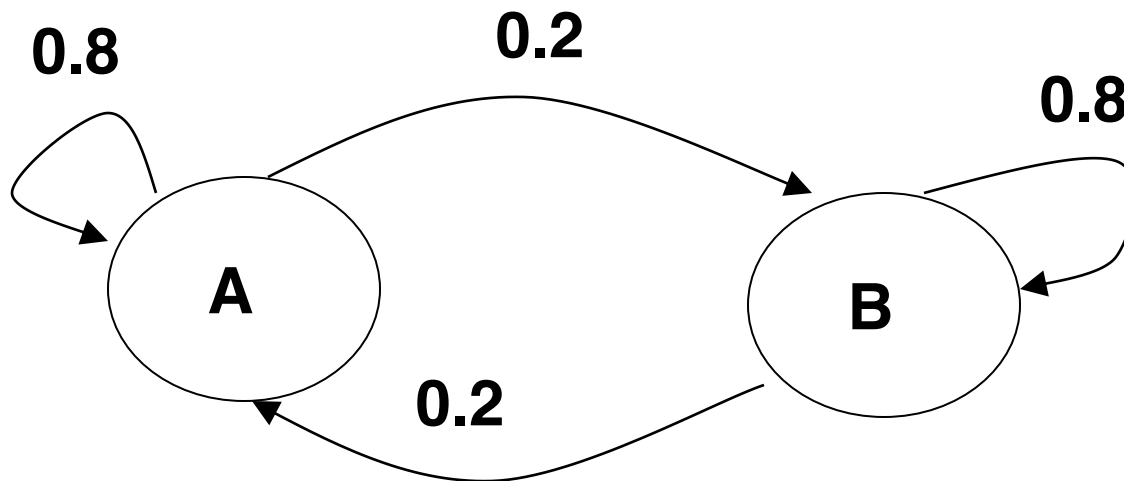
An important aspect of this definition is the Markov property: q_{t+1} is conditionally independent of q_{t-1} (and any earlier time points) given q_t

More formally $P(q_{t+1} = s_i \mid q_t = s_j) = P(q_{t+1} = s_i \mid q_t = s_j, q_{t-1} = s_j)$

What can we ask when using a HMM?

A few examples:

- “What dice is currently being used?”
- “What is the probability of a 6 in the next role?”
- “What is the probability of 6 in any of the next 3 roles?”

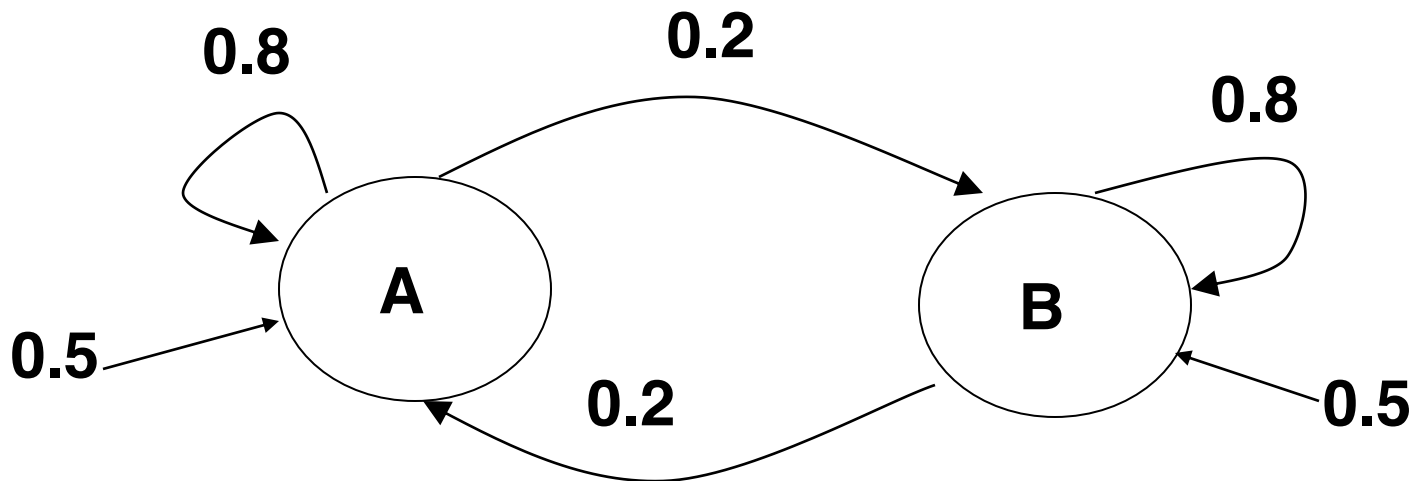


Inference in HMMs

- Computing $P(Q)$ and $P(q_t = s_i)$
 - If we cannot look at observations
- Computing $P(Q | O)$ and $P(q_t = s_i | O)$
 - When we have observation and care about the last state only
- Computing $\operatorname{argmax}_Q P(Q | O)$
 - When we care about the entire path

What dice is currently being used?

- We played t rounds so far
- We want to determine $P(q_t = A)$
- Lets assume for now that we cannot observe any outputs (we are blind folded)
- How can we compute this?



$P(q_t = A)?$

- Simple answer:

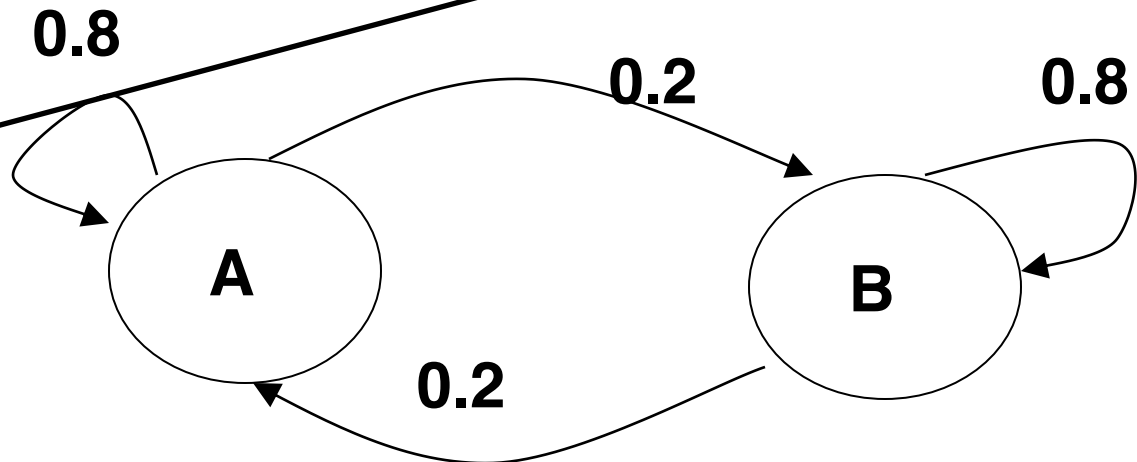
Lets determine $P(Q)$ where Q is any path that ends in A

$Q = q_1, \dots q_{t-1}, A$

$$P(Q) = P(q_1, \dots q_{t-1}, A) = P(A \mid q_1, \dots q_{t-1}) P(q_1, \dots q_{t-1}) =$$
$$P(A \mid q_{t-1}) P(q_1, \dots q_{t-1}) = \dots = P(A \mid q_{t-1}) \dots P(q_2 \mid q_1) P(q_1)$$

Markov property!

Initial probability



$P(q_t = A)?$

- Simple answer:

1. Lets determine $P(Q)$ where Q is any path that ends in A

$$Q = q_1, \dots, q_{t-1}, A$$

$$\begin{aligned} P(Q) &= P(q_1, \dots, q_{t-1}, A) = P(A \mid q_1, \dots, q_{t-1}) P(q_1, \dots, q_{t-1}) = \\ &P(A \mid q_{t-1}) P(q_1, \dots, q_{t-1}) = \dots = P(A \mid q_{t-1}) \dots P(q_2 \mid q_1) P(q_1) \end{aligned}$$

2. $P(q_t = A) = \sum P(Q)$

where the sum is over all sets of t
states that end in A

$P(q_t = A)?$

- Simple answer:

1. Lets determine $P(Q)$ where Q is any path that ends in A

$$Q = q_1, \dots, q_{t-1}, A$$

$$\begin{aligned} P(Q) &= P(q_1, \dots, q_{t-1}, A) = P(A \mid q_1, \dots, q_{t-1}) P(q_1, \dots, q_{t-1}) = \\ &P(A \mid q_{t-1}) P(q_1, \dots, q_{t-1}) = \dots = P(A \mid q_{t-1}) \dots P(q_2 \mid q_1) P(q_1) \end{aligned}$$

2. $P(q_t = A) = \sum P(Q)$

where the sum is over all sets of t states that end in A

Q: How many sets Q are there?

A: A lot! (2^{t-1})

Not a feasible solution

$P(q_t = A)$, the smart way

- Lets define $p_t(i)$ as the probability of being in state i at time t :
 $p_t(i) = p(q_t = s_i)$
- We can determine $p_t(i)$ by induction
 1. $p_1(i) = \Pi_i$
 2. $p_t(i) = ?$

$P(q_t = A)$, the smart way

- Lets define $p_t(i)$ = probability state i at time t = $p(q_t = s_i)$
- We can determine $p_t(i)$ by induction
 1. $p_1(i) = \Pi_i$
 2. $p_t(i) = \sum_j p(q_t = s_i \mid q_{t-1} = s_j) p_{t-1}(j)$

$P(q_t = A)$, the smart way

- Lets define $p_t(i) = \text{probability state } i \text{ at time } t = p(q_t = s_i)$
- We can determine $p_t(i)$ by induction
 1. $p_1(i) = \Pi_i$
 2. $p_t(i) = \sum_j p(q_t = s_i \mid q_{t-1} = s_j) p_{t-1}(j)$

This type of computation is called dynamic programming

Complexity: $O(n^2 * t)$

Number of states in our HMM

Time / state	t1	t2	t3
s1	.3		
s2	.7		

Inference in HMMs

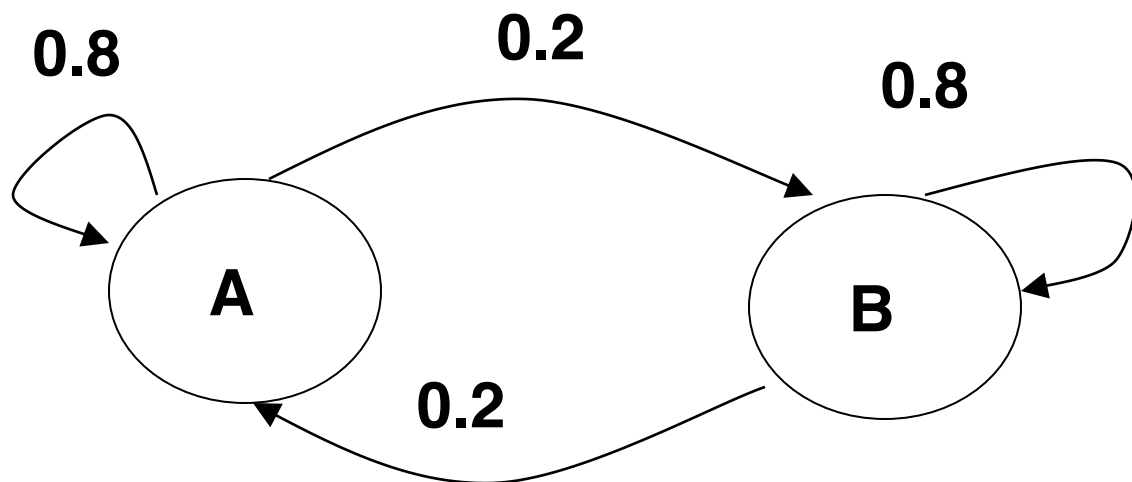
- Computing $P(Q)$ and $P(q_t = s_i)$ ✓
- Computing $P(Q | O)$ and $P(q_t = s_i | O)$
- Computing $\operatorname{argmax}_Q P(Q)$

But what if we observe outputs?

- So far, we assumed that we could not observe the outputs
- In reality, we almost always can.



v	$P(v A)$	$P(v B)$
1	.3	.1
2	.2	.1
3	.2	.1
4	.1	.2
5	.1	.2
6	.1	.3



But what if we observe outputs?

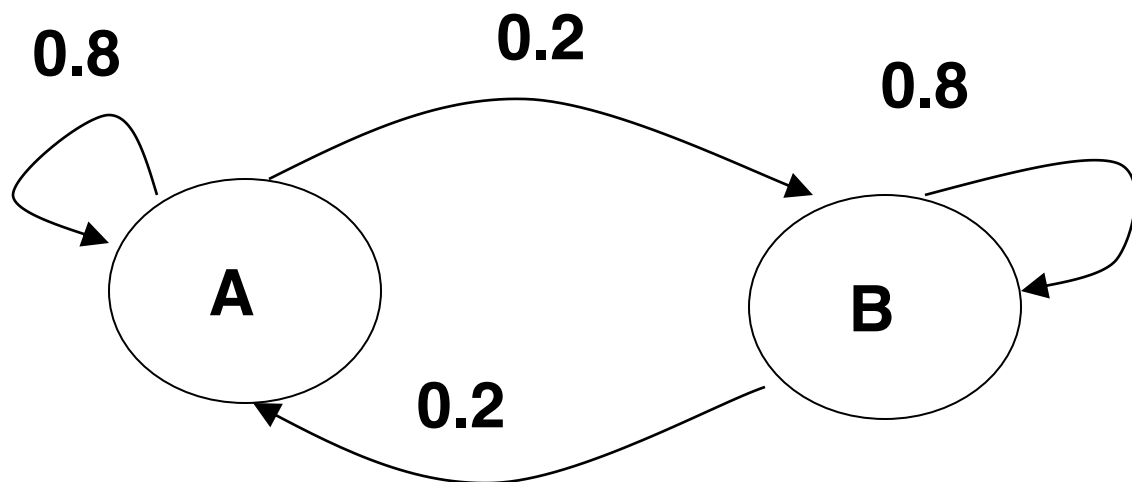
- So far, we assumed that we could not observe the outputs
- In reality, we almost a

Does observing the sequence

5, 6, 4, 5, 6, 6

Change our belief about the state?

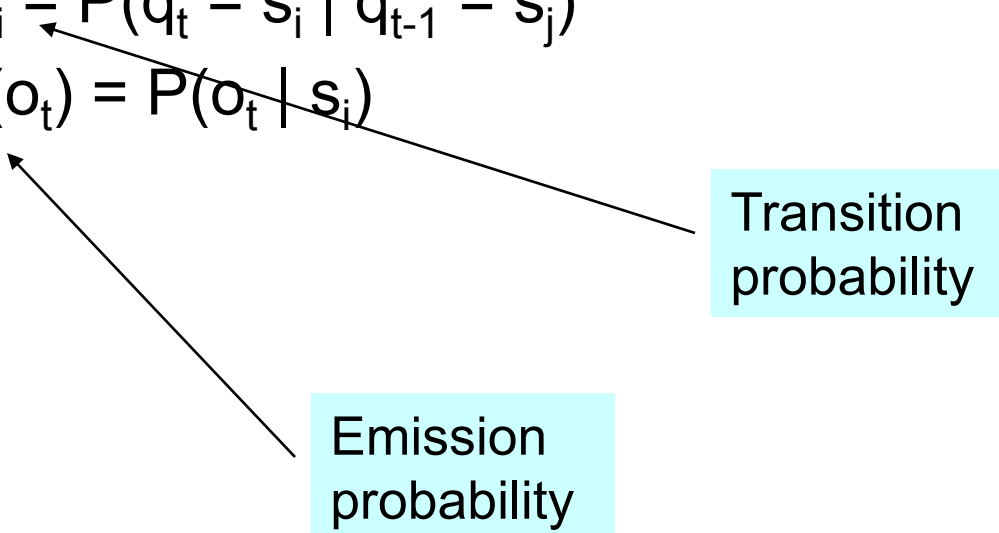
v	$P(v A)$	$P(v B)$
1	.3	.1
2	.2	.1
3	.2	.1
4	.1	.2
5	.1	.2
6	.1	.3



$P(q_t = A)$ when outputs are observed

- We want to compute $P(q_t = A \mid O_1 \dots O_t)$
- For ease of writing we will use the following notations (commonly used in the literature)
- $a_{j,i} = P(q_t = s_i \mid q_{t-1} = s_j)$
- $b_i(o_t) = P(o_t \mid s_i)$

Transition
probability



Emission
probability

$P(q_t = A)$ when outputs are observed

- We want to compute $P(q_t = A \mid O_1 \dots O_t)$
- Lets start with a simpler question. Given a sequence of states Q , what is $P(Q \mid O_1 \dots O_t) = P(Q \mid O)$?
 - It is pretty simple to move from $P(Q)$ to $P(q_t = A)$
 - In some cases $P(Q)$ is the more important question
 - Speech processing
 - NLP

$P(Q | O)$

- We can use Bayes rule:

$$P(Q|O) = \frac{P(O | Q)P(Q)}{P(O)}$$



Easy, $P(O | Q) = P(o_1 | q_1) P(o_2 | q_2) \dots P(o_t | q_t)$

$P(Q | O)$

- We can use Bayes rule:

$$P(Q|O) = \frac{P(O | Q)P(Q)}{P(O)}$$



Easy, $P(Q) = P(q_1) P(q_2 | q_1) \dots P(q_t | q_{t-1})$

$$P(Q | O)$$

- We can use Bayes rule:

$$P(Q|O) = \frac{P(O | Q)P(Q)}{P(O)}$$



Hard!

$P(O)$

- What is the probability of seeing a set of observations:
 - An important question in it own rights, for example classification using two HMMs
- Define $\alpha_t(i) = P(o_1, o_2 \dots, o_t \wedge q_t = s_i)$
- $\alpha_t(i)$ is the probability that we:
 1. Observe $o_1, o_2 \dots, o_t$
 2. End up at state i

How do we compute $\alpha_t(i)$?

Computing $\alpha_t(i)$

$$\alpha_t(i) = P(o_1, o_2, \dots, o_t \wedge q_t = s_i)$$

- $\alpha_1(i) = P(o_1 \wedge q_1 = i) = P(o_1 | q_1 = s_i) \Pi_1$

We must be at a state in time t

chain rule

Markov property

Computing $\alpha_t(i)$

$$\alpha_t(i) = P(o_1, o_2, \dots, o_t \wedge q_t = s_i)$$

- $\alpha_1(i) = P(o_1 \wedge q_1 = i) = P(o_1 \mid q_1 = s_i) \Pi_i$

$$\begin{aligned} \alpha_{t+1}(i) &= P(O_1 \dots O_{t+1} \wedge q_{t+1} = s_i) = && \text{We must be at a state in time } t \\ & \sum_j P(O_1 \dots O_t \wedge q_t = s_j \wedge O_{t+1} \wedge q_{t+1} = s_i) = && \text{chain rule} \\ & \sum_j P(O_{t+1} \wedge q_{t+1} = s_i \mid O_1 \dots O_t \wedge q_t = s_j) P(O_1 \dots O_t \wedge q_t = s_j) = \\ & \sum_j P(O_{t+1} \wedge q_{t+1} = s_i \mid O_1 \dots O_t \wedge q_t = s_j) \alpha_t(j) = && \text{Markov property} \\ & \sum_j P(O_{t+1} \mid q_{t+1} = s_i) P(q_{t+1} = s_i \mid q_t = s_j) \alpha_t(j) = \\ & \sum_j b_i(O_{t+1}) a_{j,i} \alpha_t(j) \end{aligned}$$

Example: Computing $\alpha_3(B)$

- We observed 2,3,6

$$\alpha_1(A) = P(2 \wedge q_1 = A) = P(2 \mid q_1 = A)\Pi_A = .2 * .7 = .14, \alpha_1(B) = .1 * .3 = .03$$

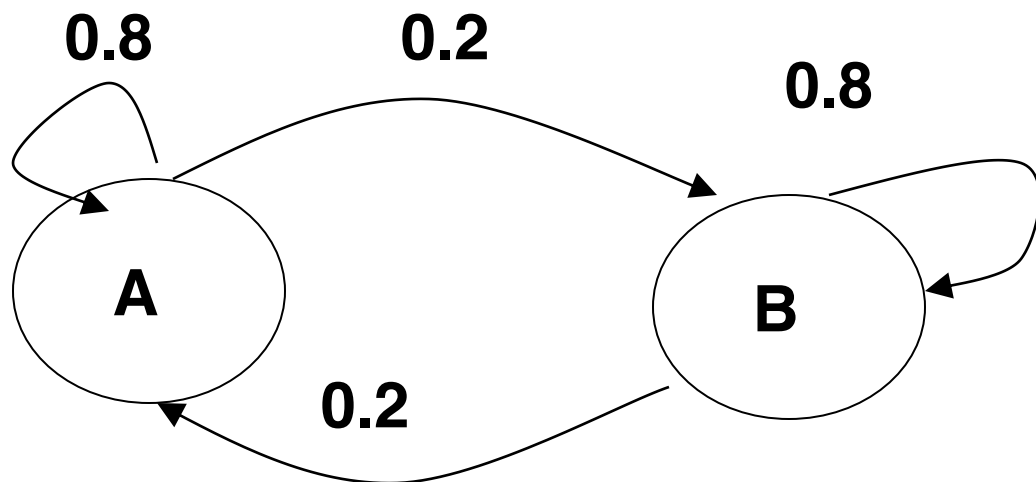
$$\alpha_2(A) = \sum_{j=A,B} b_A(3) a_{j,A} \alpha_1(j) = .2 * .8 * .14 + .2 * .2 * .03 = 0.0236, \alpha_2(B) = 0.0052$$

$$\alpha_3(B) = \sum_{j=A,B} b_B(6) a_{j,B} \alpha_2(j) = .3 * .2 * .0236 + .3 * .8 * .0052 = 0.00264$$

$$\Pi_A = 0.7$$

$$\Pi_B = 0.3$$

v	P(v A)	P(v B)
1	.3	.1
2	.2	.1
3	.2	.1
4	.1	.2
5	.1	.2
6	.1	.3



Where we are

- We want to compute $P(Q | O)$
- For this, we only need to compute $P(O)$
- We know how to compute $\alpha_t(i)$

From now its easy

$$\alpha_t(i) = P(o_1, o_2 \dots, o_t \wedge q_t = s_i)$$

so

$$P(O) = P(o_1, o_2 \dots, o_t) = \sum_i P(o_1, o_2 \dots, o_t \wedge q_t = s_i) = \sum_i \alpha_t(i)$$

note that

$$p(q_t=s_i | o_1, o_2 \dots, o_t) = \frac{\alpha_t(i)}{\sum_j \alpha_t(j)}$$


$$P(A | B) = P(A \wedge B) / P(B)$$

Complexity

- How long does it take to compute $P(Q \mid O)$?
- $P(Q)$: $O(n)$
- $P(O|Q)$: $O(n)$
- $P(O)$: $O(n^2t)$

Inference in HMMs

- Computing $P(Q)$ and $P(q_t = s_i)$ ✓
- Computing $P(Q | O)$ and $P(q_t = s_i | O)$ ✓
- Computing $\operatorname{argmax}_Q P(Q)$

Most probable path

- We are almost done ...
- One final question remains

How do we find the most probable path, that is Q^* such that

$$P(Q^* | O) = \operatorname{argmax}_Q P(Q|O)?$$

- This is an important path
 - The words in speech processing
 - The set of genes in the genome
 - etc.

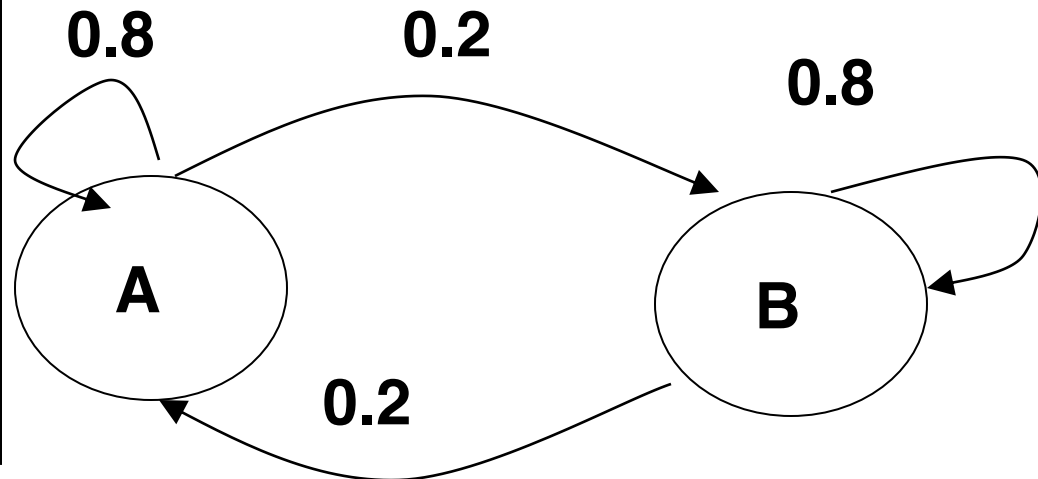
Example

- What is the most probable set of states leading to the sequence:

1,2,2,5,6,5,1,2,3 ?

$$\Pi_A = 0.7$$
$$\Pi_B = 0.3$$

v	P(v A)	P(v B)
1	.3	.1
2	.2	.1
3	.2	.1
4	.1	.2
5	.1	.2
6	.1	.3



Most probable path

$$\begin{aligned}\arg \max_Q P(Q | O) &= \arg \max_Q \frac{P(O | Q)P(Q)}{P(O)} \\ &= \arg \max_Q P(O | Q)P(Q)\end{aligned}$$

We will use the following definition:

$$\delta_t(i) = \max_{q_1 \dots q_{t-1}} p(q_1 \dots q_{t-1} \wedge q_t = s_i \wedge O_1 \dots O_t)$$

In other words we are interested in the most likely path from 1 to t that:

1. Ends in S_i
2. Produces outputs $O_1 \dots O_t$

Computing $\delta_t(i)$

$$\begin{aligned}\delta_1(i) &= p(q_1 = s_i \wedge O_1) \\ &= p(q_1 = s_i)p(O_1 | q_1 = s_i) \\ &= \pi_i b_i(O_1)\end{aligned}$$

$$\delta_t(i) = \max_{q_1 \dots q_{t-1}} p(q_1 \dots q_{t-1} \wedge q_t = s_i \wedge O_1 \dots O_t)$$

Q: Given $\delta_t(i)$, how can we compute $\delta_{t+1}(i)$?

A: To get from $\delta_t(i)$ to $\delta_{t+1}(i)$ we need to

1. Add an emission for time $t+1$ (O_{t+1})
2. Transition to state s_i

$$\begin{aligned}\delta_{t+1}(i) &= \max_{q_1 \dots q_t} p(q_1 \dots q_t \wedge q_{t+1} = s_i \wedge O_1 \dots O_{t+1}) \\ &= \max_j \delta_t(j) p(q_{t+1} = s_i | q_t = s_j) p(O_{t+1} | q_{t+1} = s_i) \\ &= \max_j \delta_t(j) a_{j,i} b_i(O_{t+1})\end{aligned}$$

The Viterbi algorithm

$$\begin{aligned}\delta_{t+1}(i) &= \max_{q_1 \dots q_t} p(q_1 \dots q_t \wedge q_{t+1} = s_i \wedge O_1 \dots O_{t+1}) \\ &= \max_j \delta_t(j) p(q_{t+1} = s_i \mid q_t = s_j) p(O_{t+1} \mid q_{t+1} = s_i) \\ &= \max_j \delta_t(j) a_{j,i} b_i(O_{t+1})\end{aligned}$$

- Once again we use dynamic programming for solving $\delta_t(i)$
- Once we have $\delta_t(i)$, we can solve for our $P(Q^*|O)$

By:

$$P(Q^* \mid O) = \operatorname{argmax}_Q P(Q|O) =$$

path defined by $\operatorname{argmax}_j \delta_t(j)$,

Inference in HMMs

- Computing $P(Q)$ and $P(q_t = s_i)$ ✓
- Computing $P(Q | O)$ and $P(q_t = s_i | O)$ ✓
- Computing $\operatorname{argmax}_Q P(Q)$ ✓

What you should know

- Why HMMs? Which applications are suitable?
- Inference in HMMs
 - No observations
 - Probability of next state w. observations
 - Maximum scoring path (Viterbi)