Exercise sheet 2: Hidden Markov models II

Exercise 1 - The occasionally cheating casino

In a casino they use a fair die most of the time, but occasionally they switch to a loaded die. The loaded die has a probability 0.5 to show number six and probability 0.1 for the numbers one to five. Assume that the casino switches from a fair to a loaded die with probability 0.05 before each roll, and that the probability of switching back is 0.1. The probability to start a game with the fair die is 0.9.

1a)

Find the probability $P(\mathcal{O}|M)$ for $\mathcal{O} = 1662$ and the given HMM using the forward algorithm.

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Hint 1 : Formulae

$$\begin{aligned}\alpha_1(i) =& \pi_i \times b_{i,o_1} \\ \alpha_{t+1}(j) =& \sum_{i \in \{F,L\}} \alpha_t(i) \times a_{i,j} \times b_{j,o_{t+1}}\end{aligned}$$

Hint 2 : Calculation Method

$$\begin{aligned}\alpha_1(F) =& \pi_F \times b_{F,1} = 0.9 \times \frac{1}{6} = 0.15 \\ \alpha_1(L) =& \pi_F \times b_{L,1} = 0.1 \times 0.1 = 0.01\end{aligned}$$

$$\begin{aligned}\alpha_2(F) =& \alpha_1(F) \times a_{F,F} \times b_{F,6} + \alpha_1(L) \times a_{L,F} \times b_{F,6} = 0.15 \times 0.95 \times \frac{1}{6} + 0.01 \times 0.1 \times \frac{1}{6} = 0.0239167 \\ \alpha_2(L) =& \alpha_1(F) \times a_{F,L} \times b_{L,6} + \alpha_1(L) \times a_{L,L} \times b_{L,6} = 0.15 \times 0.05 \times 0.5 + 0.01 \times 0.9 \times 0.5 = 0.00825 \\ \alpha_3(F) =& 0.023917 \times 0.95 \times \frac{1}{6} + 0.00825 \times 0.1 \times \frac{1}{6} = 0.00392 \\ \alpha_3(L) =& 0.023917 \times 0.05 \times 0.5 + 0.00825 \times 0.9 \times 0.5 = 0.00431 \\ \alpha_4(F) =& 0.00392 \times 0.95 \times \frac{1}{6} + 0.00431 \times 0.1 \times \frac{1}{6} = 0.000693 \\ \alpha_4(L) =& 0.00392 \times 0.05 \times 0.1 + 0.00431 \times 0.9 \times 0.1 = 0.000407\end{aligned}$$

Solution

$$P(\mathcal{O} = 1662) = \alpha_4(F) + \alpha_4(L) = 0.000693 + 0.000407 = 0.0011$$

1b)

Given the result of Question 1A, do you expect a higher probability for the observations $\mathcal{O} = 1666$ and $\mathcal{O} = 1262$?

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Hint 1 It has something to do with the emission probabilities of the different states.

Solution As state L has a high probability to emit a six, observations with more sixes are more likely.

$$P(\mathcal{O} = 1666) > P(\mathcal{O} = 1662) > P(\mathcal{O} = 1262)$$

1c)

Find the most probable path through the HMM that produces the sequence $\mathcal{O} = 1662$.

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Hint 1 : Formulae

$$\begin{aligned}
\delta_1(i) =& \pi_i \times b_{i,o_1} \\
\delta_{t+1}(j) =& max_{i \in \{F,L\}} \delta_t(i) \times a_{i,j} \times b_{j,o_{t+1}} \\
q_t^* =& argmax_{1 \leq i \leq n} \{\delta_t(i) a_{i,q_{t+1}^*}\}
\end{aligned}$$

Hint 2 : Intermediate calculations

$$\begin{aligned}
\delta_1(F) =& \pi_F \times b_{F,1} = 0.9 \times \frac{1}{6} = 0.15 \\
\delta_1(L) =& \pi_F \times b_{L,1} = 0.1 \times 0.1 = 0.01 \\
\\
\delta_2(F) =& max(\delta_1(F) \times a_{F,F} \times b_{F,6}, \delta_1(L) \times a_{L,F} \times b_{F,6}) = max(0.02375, 0.00016) = 0.02375 \\
\delta_2(L) =& max(\delta_1(F) \times a_{F,L} \times b_{L,6}, \delta_1(L) \times a_{L,L} \times b_{L,6}) = max(0.00375, 0.0045) = 0.0045 \\
\delta_3(F) =& max(0.00376, 0.000075) = 0.00376 \\
\delta_3(L) =& max(0.00059375, 0.002025) = 0.002025 \\
\delta_4(F) =& max(0.0005953, 0.00003375) = 0.0005953 \\
\delta_4(L) =& max(0.0000188, 0.00018225) = 0.00018225
\end{aligned}$$

$$P(\mathcal{P}^*, \mathcal{O}) = max(\delta_4(F), \delta_4(L)) = 5.95 \times 10^{-4}$$

Solution

$$
\begin{aligned}
q_4^* =& argmax_{i\in\{F,L\}}(\delta_4(i)) = F \\
q_3^* =& argmax_{i\in\{F,L\}}(\delta_3(i) \times a_{i,q_4^*}) = argmax(F : 0.00376 \times 0.95, L : 0.002025 \times 0.1) = F \\
q_2^* =& argmax_{i\in\{F,L\}}(\delta_2(i) \times a_{i,q_3^*}) = argmax(F : 0.02375 \times 0.95, L : 0.0045 \times 0.1) = F \\
q_1^* =& argmax_{i\in\{F,L\}}(\delta_1(i) \times a_{i,q_2^*}) = argmax(F : 0.15 \times 0.95, L : 0.01 \times 0.1) = F \\
& \Rightarrow Q^* = FFFF
\end{aligned}
$$

The best path is therefore to stay in state F.

Exercise 2 - Profile HMMs

Profile HMMs define a position specific scoring scheme which can be used to search databases for homologous sequences.

The following multiple alignment of DNA sequences is given:

```
AC---A
A----A
AG---T
TTGGGT
**   *
```

2a)

Draw the graphical representation of the profile HMM for the given multiple alignment.

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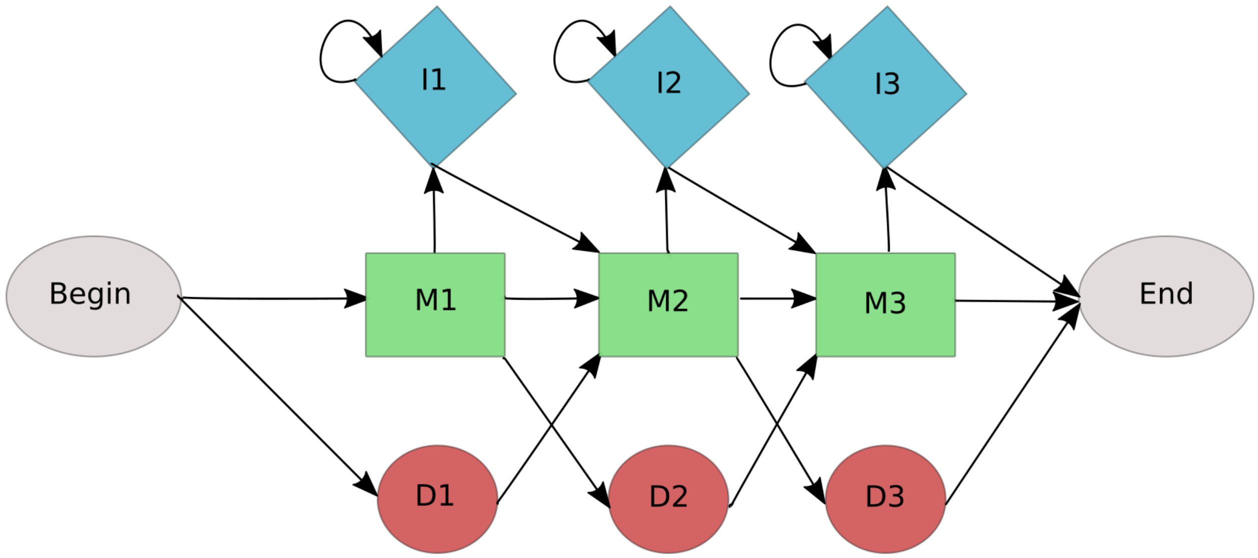
Solution



2b)

Find the state sequences that correspond to each row in the alignment.

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Solution

```
AC---A M1 M2 M3
A----A M1 D2 M3
AG---T M1 M2 M3
TTGGGT M1 M2 I2 I2 I2 M3
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2c)

Compute the following emission probabilities with maximum likelihood estimation: $b_{M_1,A}$, $b_{M_1,G}$, $b_{M_1,C}$, $b_{M_1,T}$.

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Formulae

$$b_{i,k} = \frac{E[\text{number of emissions of } \sigma_k \text{, while in state } i|\mathcal{O}, M]}{E[\text{number of times in state } i|\mathcal{O}, M]}$$

Solution $b_{M_1,A} = \frac{3}{4}$

$b_{M_1,G} = 0$

$b_{M_1,C} = 0$

$b_{M_1,T} = \frac{1}{4}$

2d)

Compute the following transition probabilities with maximum likelihood estimation: a_{M_2,M_3}, a_{M_2,I_2}, a_{M_2,D_3}

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Formulae

$$a_{i,j} = \frac{E[\text{number of transitions from } i \text{ to } j|\mathcal{O}, M]}{E[\text{number of transitions from } i|\mathcal{O}, M]}$$

Solution $a_{M_2,M_3} = \frac{2}{2+1+0} = \frac{2}{3}$

$a_{M_2,I_2} = \frac{1}{2+1+0} = \frac{1}{3}$

$a_{M_2,D_3} = \frac{0}{2+1+0} = 0$

2e)

Repeat the calculations from c) and d) using a pseudo-count of 1.

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Solution $b_{M_1,A} = \frac{3+1}{4+4} = \frac{1}{2}$

$b_{M_1,G} = \frac{0+1}{4+4} = \frac{1}{8}$

$b_{M_1,C} = \frac{0+1}{4+4} = \frac{1}{8}$

$b_{M_1,T} = \frac{1+1}{4+4} = \frac{1}{4}$

$a_{M_2,M_3} = \frac{2+1}{2+1+0+3} = \frac{1}{2}$

$a_{M_2,I_2} = \frac{1+1}{2+1+0+3} = \frac{1}{3}$

$a_{M_2,D_3} = \frac{0+1}{2+1+0+3} = \frac{1}{6}$