

# The main algorithms used in the `seqHMM` package

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May 16, 2025

## 1 Introduction

This vignette contains the descriptions of the main algorithms used in the `seqHMM` (Helske and Helske, 2019) package. First, a forward-backward algorithm is presented, followed by a Viterbi algorithm, and the derivations of the gradients for the numerical optimisation routines.

## 2 Forward–Backward Algorithm

Following Rabiner (1989), the *forward variable*

$$\alpha_{it}(s) = P(\mathbf{y}_{i1}, \dots, \mathbf{y}_{it}, z_t = s | \mathcal{M})$$

is the joint probability of partial observation sequences for subject  $i$  until time  $t$  and the hidden state  $s$  at time  $t$  given the model  $\mathcal{M}$ . Let us denote  $b_s(\mathbf{y}_{it}) = b_s(y_{it1}) \cdots b_s(y_{itC})$ , the joint emission probability of observations at time  $t$  in channels  $1, \dots, C$  given hidden state  $s$ . The forward variable can be solved recursively for subject  $i = 1, \dots, N$ :

1. Initialization: For  $s = 1, \dots, S$ , compute

$$\alpha_{i1}(s) = \pi_s b_s(\mathbf{y}_{i1})$$

2. Recursion: For  $t = 1, \dots, T - 1$ , compute

$$\alpha_{i(t+1)}(s) = \left[ \sum_{r=1}^S \alpha_{it}(r) a_{rs} \right] b_s(\mathbf{y}_{i(t+1)}), \quad s = 1, \dots, S$$

3. Termination: Compute the likelihood

$$P(Y_i | \mathcal{M}) = \sum_{s=1}^S \alpha_{iT}(s)$$

The *backward variable*

$$\beta_{it}(s) = P(\mathbf{y}_{i(t+1)}, \dots, \mathbf{y}_{iT} | z_t = s, \mathcal{M})$$

is the joint probability of the partial observation sequence after time  $t$  and hidden state  $s$  at time  $t$  given the model  $\mathcal{M}$ . For subject  $i = 1, \dots, N$ , the backward variable can be computed as

1. Initialization: For  $s = 1, \dots, S$ , set

$$\beta_{iT}(s) = 1$$

2. Recursion: For  $t = T - 1, \dots, 1$ , compute

$$\beta_{it}(s) = \sum_{r=1}^S [a_{sr} b_r(\mathbf{y}_{i(t+1)}) \beta_{i(t+1)}(r)], \quad s = 1, \dots, S$$

In practice the forward-backward algorithm is prone to numerical instabilities. Typically we scale the forward and backward probabilities, as follows (Rabiner, 1989). For subject  $i = 1, \dots, N$ ,

1. Initialization: For  $s = 1, \dots, S$ , compute

$$\begin{aligned} \alpha_{i1}(s) &= \pi_s b_s(\mathbf{y}_{i1}), \\ c_{i1} &= 1 / \sum_{s=1}^S \alpha_{i1}(s), \\ \hat{\alpha}_{i1} &= c_{i1} \alpha_{i1} \end{aligned}$$

2. Recursion: For  $t = 1, \dots, T - 1$ , compute (as before)

$$\alpha_{i(t+1)}(s) = \left[ \sum_{r=1}^S \alpha_{it}(r) a_{rs} \right] b_s(\mathbf{y}_{i(t+1)}), \quad s = 1, \dots, S$$

and scale as

$$\begin{aligned} c_{i(t+1)} &= 1 / \sum_{s=1}^S \alpha_{i(t+1)}(s), \\ \hat{\alpha}_{i(t+1)} &= c_{i(t+1)} \alpha_{i(t+1)} \end{aligned}$$

3. Termination: Compute the log-likelihood

$$\log P(Y_i | \mathcal{M}) = - \sum_{t=1}^T c_{it}$$

The scaling factors  $c_{it}$  from the forward algorithm are commonly used to scale also the backward variables, although other scaling schemes are possible as well. In `seqHMM`, the scaled backward variables for subject  $i = 1, \dots, N$  are computed as

1. Initialization: For  $s = 1, \dots, S$ , compute

$$\hat{\beta}_{iT}(s) = c_{iT}$$

2. Recursion: For  $t = T - 1, \dots, 1$ , and  $r = 1, \dots, S$ , compute and scale

$$\beta_{it}(s) = \sum_{r=1}^S [a_{sr} b_r(\mathbf{y}_{i(t+1)}) \beta_{i(t+1)}(r)], \quad s = 1, \dots, S$$

$$\hat{\beta}_{it}(s) = c_{it} \beta_{it}(s)$$

Most of the times this scaling method described works well, but in some ill-conditioned cases it is possible that the default scaling still produces underflow in backward algorithm. For these cases, `seqHMM` also supports the computation of the forward and backward variables in log-space. Although numerically more stable, the algorithm is somewhat slower due repeated use of log-sum-exp trick.

### 3 Viterbi Algorithm

We define the score

$$\delta_{it}(s) = \max_{z_{i1} z_{i2} \dots z_{it}} P(z_{i1} \dots z_{it} = s, \mathbf{y}_{i1} \dots \mathbf{y}_{it} | \mathcal{M}),$$

which is the highest probability of the hidden state sequence up to time  $t$  ending in state  $s$ . By induction we have

$$\delta_{i(t+1)}(r) = \left[ \max_s \delta_{it}(s) a_{sr} \right] b_r(\mathbf{y}_{i(t+1)}). \quad (1)$$

We collect the arguments maximizing Equation 1 in an array  $\psi_{it}(r)$  to keep track of the best hidden state sequence. The full Viterbi algorithm can be stated as follows:

1. Initialization

$$\delta_{i1}(s) = \pi_s b_s(\mathbf{y}_{i1}), s = 1, \dots, S$$

$$\psi_{i1}(s) = 0$$

2. Recursion

$$\delta_{it}(r) = \max_{s=1, \dots, S} (\delta_{i(t-1)}(s) a_{sr}) b_h(\mathbf{y}_{it}),$$

$$\psi_{it}(s) = \arg \max_{s=1, \dots, S} (\delta_{i(t-1)}(s) a_{sr}), s = 1, \dots, S; t = 2, \dots, T$$

3. Termination

$$\hat{P} = \max_{s=1, \dots, S} (\delta_{iT}(s))$$

$$\hat{z}_{iT} = \arg \max_{s=1, \dots, S} (\delta_{iT}(s))$$

4. Sequence backtracking

$$\hat{z}_{it} = \psi_{i(t+1)}(\hat{s}_{i(t+1)}), t = T - 1, \dots, 1.$$

To avoid numerical underflow due to multiplying many small probabilities, the Viterbi algorithm can be straightforwardly computed in log space, i.e., calculating  $\log(\delta_{it}(s))$ .

## 4 Gradients

Following Levinson, Rabiner, and Sondhi (1983), by using the scaled forward and backward variables we have

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial \pi_s} = b_s(\mathbf{y}_{i1})\hat{\beta}_{i1}(s),$$

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial a_{sr}} = \sum_{t=1}^{T-1} \hat{\alpha}_{it}(s)b_r(\mathbf{y}_{i(t+1)})\hat{\beta}_{i(t+1)}(r),$$

and

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial b_{rc}(m)} = \sum_{t:y_{itc}=m} \sum_{s=1}^S \alpha_{it}(s)a_{sr}\hat{\beta}_{i(t+1)}(r) + \mathbf{I}(y_{i1c} = m)\pi_r\hat{\beta}_{i1}(r).$$

In the direct numerical optimization algorithms used by `seqHMM`, the model is parameterised using unconstrained parameters  $\pi'_s, a'_{sr}, b'_{rc}(m)$  such that  $a_{sr} = \exp(a'_{sr}) / \sum_{k=1}^S \exp(a'_sk)$ , and similarly for emission and initial probabilities. This leads to

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial \pi'_s} = \frac{\partial \log P(Y_i|\mathcal{M})}{\partial \pi_s} \pi_s(1 - \pi_s)$$

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial a'_{sr}} = \frac{\partial \log P(Y_i|\mathcal{M})}{\partial a_{sr}} a_{sr}(1 - a_{sr}),$$

and

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial b'_{rc}(m)} = \frac{\partial \log P(Y_i|\mathcal{M})}{\partial b_{rc}(m)} b_{rc}(m)(1 - b_{rc}(m)).$$

### 4.1 MHMM case

For mixture HMM with  $K$  clusters, we define a full model with  $S = S^1 + \dots + S^K$  states in a block form with  $\pi_i = (w_{i1}\pi^1, \dots, w_{iK}\pi^K)^\top$ , where  $\pi^k$ ,  $k = 1, \dots, K$  is the vector of initial probabilities for the submodel  $\mathcal{M}^k$  and  $w_{ik} = \exp(\mathbf{x}_i^\top \gamma_k) / (1 + \sum_{j=2}^K \exp(\mathbf{x}_i^\top \gamma_j))$ , with  $\gamma_1 = 0$ .

First note that the log-likelihood of the HMM for  $i$ th subject can be written as

$$P(Y_i|\mathcal{M}) = \sum_{s=1}^S \sum_{r=1}^S \alpha_t(s)a_{sr}b_r(\mathbf{y}_{i(t+1)})\beta_{t+1}(r),$$

for any  $t = 1, \dots, T - 1$ . Thus for  $t = 1$  we have

$$\begin{aligned}
P(Y_i|\mathcal{M}) &= \sum_{s=1}^S \sum_{r=1}^S \alpha_1(s) a_{sr} b_r(\mathbf{y}_{i2}) \beta_2(r) \\
&= \sum_{s=1}^S \alpha_1(s) \sum_{r=1}^S a_{sr} b_r(\mathbf{y}_{i2}) \beta_2(r) \\
&= \sum_{s=1}^S \alpha_1(s) \beta_1(s) \\
&= \sum_{s=1}^S \pi_{is} b_s(\mathbf{y}_{i1}) \beta_1(s).
\end{aligned} \tag{2}$$

Therefore the gradients for the unconstrained parameters  $\pi_s^{k'}$  of the  $k$ th cluster are given as

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial \pi_s^{k'}} = \frac{\partial \log P(Y_i|\mathcal{M}^k)}{\partial \pi_s^k} \pi_s^k (1 - \pi_s^k) w_{ik}.$$

For  $\gamma^k$ , the gradients are of form

$$\frac{\partial \log P(Y_i|\mathcal{M})}{\partial \gamma^k} = \sum_{s=1}^S b_s(\mathbf{y}_{i1}) \hat{\beta}_1(s) \frac{\pi_{is}}{\partial \gamma_k}. \tag{3}$$

Now if state  $s$  belongs to cluster  $k$ , we have

$$\begin{aligned}
\frac{\partial \pi_{is}}{\partial \gamma_k} &= \pi_s^k \frac{\partial}{\partial \gamma_k} \frac{\exp(\mathbf{x}_i^\top \gamma_k)}{\sum_{j=1}^K \exp(\mathbf{x}_i^\top \gamma_j)} \\
&= \pi_s^k \mathbf{x}_i^\top w_{ik} (1 - w_{ik}),
\end{aligned} \tag{4}$$

and

$$\frac{\partial \pi_{is}}{\partial \gamma_k} = -\pi_s^h \mathbf{x}_i^\top w_{ih} w_{ik},$$

otherwise, where  $h$  is the index of cluster containing the state  $s$ .

## References

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