Gradient ascent for maximum likelihood estimation in the CSM model

$$p(X \mid C_{1..K}) = \prod_{n=1}^{N} p(x_n \mid C_{1..K}) \tag{1}$$

$$p(X \mid C_{1..K}) = \prod_{n=1}^{N} \iiint_{-\infty}^{\infty} p(x_n, v_n \mid z_n, g_n) p(g_n) p(z_n) \mathrm{d}v_n \mathrm{d}g_n \mathrm{d}z_n \tag{2}$$

approximation of some of the integrals by samples from the priors $p(g_n)$ and $p(z_n)$

$$p(X \mid C_{1..K}) \approx \prod_{n=1}^{N} \sum_{l=1}^{L} \int_{-\infty}^{\infty} p(x_n, v_n \mid z_n^l, g_n^l) \mathrm{d}v_n \tag{3}$$

the integral evaluates as follows

$$\int_{-\infty}^{\infty} p(x_n, v_n \mid z_n, g_n) \mathrm{d}v_n = \frac{1}{z^{D_v} \sqrt{\det(A^T A)}} \mathcal{N}(\frac{1}{z} A^+ x; 0, \frac{\sigma_x}{z^2}(A^T A)^{-1} + \sum_{k=1}^{K} g_k U_k^T U_k) \tag{4}$$

$$f(x, z) \equiv \frac{1}{z} A^+ x \tag{5}$$

$$C(x, z, g) \equiv \frac{\sigma_x}{z^2}(A^T A)^{-1} + \sum_{k=1}^{K} g_k U_k^T U_k \tag{6}$$

$$h(z) \equiv \frac{1}{z^{D_v} \sqrt{\det(A^T A)}} \tag{7}$$

thus, the likelihood can be expressed as

$$p(X \mid C_{1..K}) \approx \prod_{n=1}^{N} \sum_{l=1}^{L} h(z_n^l) \mathcal{N}(f(x_n, z_n^l); 0, C(x_n, z_n^l, g_n^l)) \tag{8}$$

$$\log p(X \mid C_{1..K}) \approx \sum_{n=1}^{N} \log \left[\sum_{l=1}^{L} h(z_n^l) \mathcal{N}(f(x_n, z_n^l); 0, C(x_n, z_n^l, g_n^l)) \right] \tag{9}$$

$$h_n^l \equiv h(z_n^l),\ \ f_n^l \equiv f(x_n, z_n^l),\ \ C_n^l \equiv C(x_n, z_n^l, g_n^l) \tag{10}$$

$$\mathcal{L}_n^l \equiv h_n^l \mathcal{N}(f_n^l; 0, C_n^l),\ \ \mathcal{L}_n \equiv \sum_{l=1}^{L} \mathcal{L}_n^l \tag{11}$$

$$\log p(X \mid C_{1..K}) \approx \sum_{n=1}^{N} \log \mathcal{L}_n \tag{12}$$

the derivative of the likelihood with respect to a single element of the Cholesky decomposition of one of the covariance components can be decomposed this way

$$\begin{aligned} \frac{\partial \log p(X \mid C_{1..K})}{\partial \left[U_k\right]_{i,j}} \approx \sum_{n=1}^{N} \frac{\partial \log \mathcal{L}_n}{\partial \left[U_k\right]_{i,j}} = \sum_{n=1}^{N} \frac{1}{\mathcal{L}_n} \frac{\partial \mathcal{L}_n}{\partial \left[U_k\right]_{i,j}} = \sum_{n=1}^{N} \frac{1}{\mathcal{L}_n} \sum_{l=1}^{L} \frac{\partial \mathcal{L}_n^l}{\partial \left[U_k\right]_{i,j}} = \\ = \sum_{n=1}^{N} \frac{1}{\mathcal{L}_n} \sum_{l=1}^{L} \operatorname{Tr} \left[\frac{\partial \mathcal{L}_n^l}{\partial C_n^l} \frac{\partial C_n^l}{\partial \left[U_k\right]_{i,j}} \right] \end{aligned} \tag{13}$$

the derivatives in this formula are the following

$$\begin{aligned} \frac{\partial \mathcal{L}_n^l}{\partial C_n^l} = h_n^l \frac{\partial}{\partial C_n^l} \mathcal{N}(f_n^l; 0, C_n^l) = h_n^l \mathcal{N}(f_n^l; 0, C_n^l) \frac{\partial}{\partial C_n^l} \log \mathcal{N}(f_n^l; 0, C_n^l) = \\ = -\frac{h_n^l}{2} \mathcal{N}(f_n^l; 0, C_n^l) \left[(C_n^l)^{-1} - (C_n^l)^{-1} f_n^l (f_n^l)^T (C_n^l)^{-1} \right] \end{aligned} \tag{14}$$

$$\frac{\partial C(x, z, g)}{\partial \left[U_k\right]_{i,j}} = g_k \frac{\partial \left(U_k^T U_k\right)}{\partial \left[U_k\right]_{i,j}} = g_k \left(U_k^T J^{ij} + J^{ji} U_k \right) \equiv g_k \hat{U}_k^{ij} \tag{15}$$

substituting back to the derivative

$$\begin{aligned} \frac{\partial \log p(X \mid C_{1..K})}{\partial \left[U_k\right]_{i,j}} \approx \\ \approx -\frac{1}{2} \sum_{n=1}^{N} \frac{1}{\mathcal{L}_n} \sum_{l=1}^{L} h_n^l (g_n^l)_k \mathcal{N}(f_n^l; 0, C_n^l) \operatorname{Tr} \left[\left[(C_n^l)^{-1} - (C_n^l)^{-1} f_n^l (f_n^l)^T (C_n^l)^{-1} \right] \hat{U}_k^{ij} \right] = \\ = -\frac{1}{2} \operatorname{Tr} \left[\sum_{n=1}^{N} \left(\frac{1}{\mathcal{L}_n} \sum_{l=1}^{L} h_n^l (g_n^l)_k \mathcal{N}(f_n^l; 0, C_n^l) \left[(C_n^l)^{-1} - (C_n^l)^{-1} f_n^l (f_n^l)^T (C_n^l)^{-1} \right] \right) \hat{U}_k^{ij} \right] \end{aligned} \tag{16}$$

The regularities of the $\hat{U}_k$ matrices allow us to replace the trace with a much more efficient computation:

$$M_k = -\frac{1}{2}\sum_{n=1}^{N}\left(\frac{1}{\mathcal{L}_n}\sum_{l=1}^{L} h_n^l (g_n^l)_k \mathcal{N}(f_n^l; 0, C_n^l)\left[(C_n^l)^{-1} - (C_n^l)^{-1} f_n^l (f_n^l)^T (C_n^l)^{-1}\right]\right) \quad (17)$$

$$\frac{\partial \log p(X \mid C_{1..K})}{\partial \left[U_k\right]_{i,j}} \approx \mathrm{Tr}\left[M_k \hat{U}_k^{ij}\right] \quad (18)$$

$$\frac{\partial \log p(X \mid C_{1..K})}{\partial \left[U_k\right]_{i,j}} \approx \sum_{a=1}^{Dv} \left[M_k\right]_{j,a}\left[U_k\right]_{i,a} + \left[M_k\right]_{a,j}\left[U_k\right]_{i,a} \quad (19)$$

we can move the parameters in the direction of the gradient scaled by a learning rate

$$\left[U_k\right]_{i,j} \leftarrow \left[U_k\right]_{i,j} + \epsilon \frac{\partial \log p(X \mid C_{1..K})}{\partial \left[U_k\right]_{i,j}} \quad (20)$$