Graphic Lasso: two precision matrices

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1 Consistency

Suppose K categories are clustered by two groups with precision matrices Θ_1, Θ_2. The model becomes

$$\Omega^k = \boldsymbol{I}_k \Theta_1 + (1 - \boldsymbol{I}_k)\Theta_2, \quad k = 1, ..., K,$$

where $\boldsymbol{I}_k = \boldsymbol{I}(k\text{-th category belongs to group 1})$ are indicator functions. The model is identifiable since the indicator functions can be replaced by a membership matrix. Consider the optimization problem

$$\begin{aligned} \min_{\Theta_1, \Theta_2, \boldsymbol{I}_k} \quad & \sum_{k=1}^{K} \mathrm{tr}(S^k \Omega^k) - \log |\Omega^k| \\ s.t. \quad & \Omega^k = \boldsymbol{I}_k \Theta_1 + (1 - \boldsymbol{I}_k)\Theta_2, \quad k = 1, ..., K, \\ & \|\Theta_i\|_0 \leq b, \quad i = 1, 2. \end{aligned}$$

Theorem 1.1. *Let $(\Theta_1, \Theta_2, \boldsymbol{I}_k)$ be the true precision matrices and the membership. Suppose $0 < \tau_1 < \phi_{min}(\Theta_i) \leq \phi_{max}(\Theta_0) < \tau_2 < \infty$, where $i = 1, 2$ and τ_1, τ_2 are positive constants. For the estimation $(\hat{\Theta}_1, \hat{\Theta}_2, \hat{I}_k)$ such that $\sum_{k=1}^{K} tr(S^k \hat{\Omega}^k) - \log |\hat{\Omega}^k| \leq \sum_{k=1}^{K} tr(S^k \Omega^k) - \log |\Omega^k|$, we have the following accuracy with probability tending to 1*

$$\sum_{k=1}^{K} \left\| \hat{\Omega}^k - \Omega^k \right\| \leq 2KC'' \left[C\sqrt{\frac{b \log p}{n}} + C'\sqrt{\frac{p \log p}{n}} \right]. \tag{1}$$

Proof. Let Σ^1, Σ^2 denote the true covariance matrices. Define the sets $A_{11} = \{k : \hat{I}_k = I_k = 1\}, A_{12} = \{k : \hat{I}_k = 1, I_k = 0\}, A_{21} = \{k : \hat{I}_k = 0, I_k = 1\}$ and $A_{22} = \{k : \hat{I}_k = I_k = 0\}$. Correspondingly, we define $\Delta_{11} = \hat{\Theta}_1 - \Theta_1$, $\Delta_{12} = \hat{\Theta}_1 - \Theta_2$, $\Delta_{21} = \hat{\Theta}_2 - \Theta_1$, and $\Delta_{22} = \hat{\Theta}_2 - \Theta_2$. Let $\Delta^k = \hat{\Omega}^k - \Omega \in \{\Delta_{11}, \Delta_{12}, \Delta_{21}, \Delta_{22}\}$. The value of Δ^k depends on the true and estimated membership of k. Consider the function

$$G(\Delta_{11}, \Delta_{12}, \Delta_{21}, \Delta_{22}) = I_1 + I_2,$$

where

$$\begin{aligned} I_1 &= \sum_{k \in A_{11}} \mathrm{tr}((S^k - \Sigma^1)\Delta_{11}) + \sum_{k \in A_{12}} \mathrm{tr}((S^k - \Sigma^2)\Delta_{12}) + \sum_{k \in A_{21}} \mathrm{tr}((S^k - \Sigma^1)\Delta_{21}) + \sum_{k \in A_{22}} \mathrm{tr}((S^k - \Sigma^2)\Delta_{22}) \\ &= I_{11} + I_{12} + I_{21} + I_{22}, \end{aligned}$$

and

$$I_2 = |A_{11}|f(\Delta_{11},\Theta_1) + |A_{12}|f(\Delta_{12},\Theta_2) + |A_{21}|f(\Delta_{21},\Theta_1) + |A_{22}|f(\Delta_{22},\Theta_2),$$

with $f(\Delta,\Theta) = (\tilde{\Delta})^T \int_0^1 (1-v)(\Theta+v\Delta)^{-1} \otimes (\Theta+v\Delta)^{-1} dv \tilde{\Delta}$.

Recall the result in the common precision matrix case. For each $I_{ij}, i,j = 1,2$, we have

$$\frac{1}{|A_{ij}|}|I_{ij}| = \mathrm{tr}\left(\left(\frac{1}{|A_{ij}|}\sum_{k\in A_{ij}} S^k - \Sigma^j\right)\Delta_{ij}\right) \le C_{ij}\sqrt{\frac{\log p}{n|A_{ij}|}}|\Delta_{ij}^-|_1 + C'_{ij}\sqrt{\frac{p\log p}{n|A_{ij}|}}\left\|\Delta_{ij}\right\|_F.$$

Let $T_j = \{(k,l) : \Theta_{j,kl} \neq 0\}, j = 1,2$. We have $|\Delta_{ij}^-|_1 = |\Delta_{T_j,ij}^-|_1 + |\Delta_{T_j^c,ij}^-|_1$. Note that $|\Delta_{T_j,ij}^-|_0, |\Delta_{T_j^c,ij}^-|_0 \le b$ and $|\Delta_{T_j,ij}^-|_1, |\Delta_{T_j^c,ij}^-|_1 \le \sqrt{b}\left\|\Delta_{ij}\right\|_F$. Then, we have

$$|I_{ij}| \le \sqrt{|A_{ij}|}\left[C_{ij}\sqrt{\frac{b\log p}{n}} + C'_{ij}\sqrt{\frac{p\log p}{n}}\right]\left\|\Delta_{ij}\right\|_F.$$

On the other hand, the lower bound for I_2 is

$$I_2 \le \frac{1}{4\tau_2^2}\sum_{ij}|A_{ij}|\left\|\Delta_{ij}\right\|_F^2.$$

To let $G \le 0$, we have $I_2 \le |I_1| \le \sum_{ij}|I_{ij}|$. Plug the upper bound for $|I_{ij}|$ and the lower bound for I_2, we have

$$\frac{1}{4\tau_2^2}\sum_{ij}|A_{ij}|\left\|\Delta_{ij}\right\|_F^2 \le \left[C\sqrt{\frac{b\log p}{n}} + C'\sqrt{\frac{p\log p}{n}}\right]\sum_{ij}\sqrt{|A_{ij}|}\left\|\Delta_{ij}\right\|_F.$$

Multiply $\max|A_{ij}|$ on both sides. By Cauchy Schwartz inequality, we have

$$\max|A_{ij}|\sum_{ij}|A_{ij}|\left\|\Delta_{ij}\right\|_F^2 \ge \sum_{ij}|A_{ij}|^2\left\|\Delta_{ij}\right\|_F^2 \ge \frac{1}{4}(\sum_{ij}|A_{ij}|\left\|\Delta_{ij}\right\|_F)^2,$$

and

$$\max|A_{ij}|\sum_{ij}\sqrt{|A_{ij}|}\left\|\Delta_{ij}\right\|_F \le \frac{\max|A_{ij}|}{\sqrt{\min|A_{ij}|}}\sum_{ij}|A_{ij}|\left\|\Delta_{ij}\right\|_F.$$

Therefore, we obtain the accuracy

$$\sum_{k=1}^K\left\|\hat{\Omega}^k - \Omega^k\right\|_F = \sum_{ij}|A_{ij}|\left\|\Delta_{ij}\right\|_F \le \frac{4\max|A_{ij}|C''}{\sqrt{\min|A_{ij}|}}\left[C\sqrt{\frac{b\log p}{n}} + C'\sqrt{\frac{p\log p}{n}}\right].$$

□

Remark 1. In two group case, assuming $|A_{ij}| > 0$ for all $i,j = 1,2$, we have $\frac{\max|A_{ij}|}{\sqrt{\min|A_{ij}|}} \le \frac{K}{2}$. Then, we obtain the accuracy (1) in Theorem 1.1. If we have r groups and each group has equal number of categories, the number 4 should be replaced by $r(r-1)$ and $\frac{\max|A_{ij}|}{\sqrt{\min|A_{ij}|}} \le \frac{K}{r}$. Thus the accuracy is of order $\mathcal{O}(Kr)$.