

Topic 19: Community Detection

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Key points: .

Disclaimer: The note is built on Prof. *Jinchi Lv*'s lectures of the course at USC, DSO 607, High-Dimensional Statistics and Big Data Problems.

19.1 Stochastic Block Model (Abbe et al., 2015)

Consider an undirected graph G , with nodes V and edges E . Let

- n be a positive integer: the number of **vertices**
- k be a positive integer: the number of **communities**
- $p = (p_1, \dots, p_k)$ be a probability vector on $\{1, \dots, k\} := [k]$: the **prior** on the k communities
- \mathbf{W} be a $k \times k$ symmetric matrix with entries $W_{ij} \in [0, 1]$: the matrix of **connectivity probabilities**

then we have

Definition 19.1.1: Stochastic Block Model

The pair (\mathbf{X}, G) is drawn under $SBM(n, p, \mathbf{W})$ if \mathbf{X} is an n dimensional random vector with i.i.d. components distributed under p , and G is an n -vertex simple graph where vertices i and j are connected with probability W_{X_i, X_j} , **independently** of other pairs of vertices. And the **community** sets can be defined by

$$\Omega_i = \Omega_i(\mathbf{X}) := \{v \in [n] : X_v = i\}, i \in [k]$$

Immediately, we can define the symmetry of SBM as:

Definition 19.1.2: Symmetric SBM

An SBM is called symmetric if

- p is **uniform**
- \mathbf{W} takes the same value **on the diagonal** and the same value **off the diagonal**

(\mathbf{X}, G) is drawn under $SSBM(n, k, A, B)$ if $p = \{1/k\}^k$ and \mathbf{W} takes value A on the diagonal and B off the diagonal.

19.1.1 Recovery

The goal of community detection is to recover the labels \mathbf{X} by observing G , up to some level of accuracy. First, define **agreement** as

Definition 19.1.3: Agreement of Communities

The agreement between two community vectors $\mathbf{x}, \mathbf{y} \in [k]^n$ is obtained by maximizing the common components between \mathbf{x} and any relabelling of \mathbf{y} , that is

$$A(\mathbf{x}, \mathbf{y}) = \max_{\pi \in S_k} \frac{1}{n} \sum_{i=1}^n \mathbf{1}[x_i = \pi(y_i)]$$

where S_k is the group of permutations on $[k]$.

The **relabelling** permutation is used to handle symmetric communities such as in SSBM, as it is impossible to recover the actual labels in this case. But it's possible to recover the **partition**. There are 2 types of partition recovery we consider

Exact Recovery First, consider the case of **exact recovery**:

Definition 19.1.4: Exact Recovery

Let $(\mathbf{X}, G) \sim \text{SBM}(n, p, W)$, the exact recovery is solved if there exists an algorithm that takes G as an input and outputs $\hat{\mathbf{X}} = \hat{\mathbf{X}}(G)$ such that $\mathbb{P}\{A(\mathbf{X}, \hat{\mathbf{X}}) = 1\} = 1 - o_p(1)$

In the SSBM case, algorithms that guarantee

$$A(\mathbf{X}, \hat{\mathbf{X}}) \rightarrow \frac{1}{k}$$

would be trivial.

Weak Recovery On the other hand, we the case of **weak recovery** defined as

Definition 19.1.5: Weak Recovery

Weak recovery or detection is solved $\text{SSBM}(n, k, A, B)$ if for $(\mathbf{X}, G) \sim \text{SSBM}(n, k, A, B)$, then $\exists \epsilon > 0$ and an algorithm that takes G as an input and outputs $\hat{\mathbf{X}}$ such that

$$\mathbb{P}\left\{A(\mathbf{X}, \hat{\mathbf{X}}) \geq \frac{1}{k} + \epsilon\right\} = 1 - o(1)$$

19.1.2 Example: SSBM(n,2)

Let's look at the example of $\text{SSBM}(n, 2, \alpha \frac{\log n}{n}, \beta \frac{\log n}{n})$, where

- n : number of vertices (assumed to be even for simplicity)
- for each $v \in [n]$, a binary label X_v is attached s.t.

$$|\{v \in [n] : X_v = 1\}| = n/2$$

- for each pair of distinct nodes $u, v \in [n]$, an edge is placed with probability

- $\alpha \frac{\log n}{n}$ if $X_u = X_v$
- $\beta \frac{\log n}{n}$ if $X_u \neq X_v$

where edges are placed independently conditionally on the vertex labels

- WLOG, $\alpha > \beta$

then we have the following theorem

Theorem 19.1.6: Exact Recovery in $SSBM(n, 2, \alpha \log(n)/n, \beta \log(n)/n)$

- Exact recovery in $SSBM(n, 2, \alpha \log(n)/n, \beta \log(n)/n)$ is solvable and efficiently so if $|\sqrt{\alpha} - \sqrt{\beta}| > \sqrt{2}$ nad unsolvable if $|\sqrt{\alpha} - \sqrt{\beta}| < \sqrt{2}$
- Exact recovery of the ground truth assignment of the partition (A, B) is also achievable, that is: if

$$\frac{\alpha + \beta}{2} - \sqrt{\alpha\beta} > 1$$

i.e.

$$\alpha + \beta > 2, (\alpha - \beta)^2 > 4(\alpha + \beta) - 4$$

the maximum likelihood estimator exactly recovers the communities (up to a global flip), with high probability.

See [Abbe \(2017\)](#) for the proof of this theorem.

In summary, for a graph structure $G = (V, E)$ represented by adjacency matrix $\mathbf{X}_{n \times n}$, Stochastic Block Model (SBM)

- assumes that there is a symmetric matrix $\mathbf{P} = \{p_{ij}\} \in \mathbb{R}^{k \times k}$, for $k \ll n$ and a map $C : \{1, \dots, n\} \rightarrow \{1, \dots, k\}$, s.t. $\Pr(\mathbf{X}_{ij} = 1) = \mathbf{P}_{C(i), C(j)}$
- Define $\mathbf{\Pi} = (\pi_1, \dots, \pi_n)' \in \mathbb{R}^{n \times k}$ where $\Pi_{ij} = 1$ if $C(i) = j$, and $\Pi_{ij} = 0$ otherwise
- Let $\mathbf{H} = \mathbb{E}(\mathbf{X})$ be the probability matrix, then $\mathbf{H} = \mathbf{\Pi} \mathbf{\Pi}'$
- A variant of SBM is degree corrected SBM which incorporates the degree heterogeneity.
 - each node is assigned a parameter $\theta_i > 0$ such that $\Pr(\mathbf{X}_{ij} = 1) = \theta_i \theta_j \mathbf{P}_{C(i), C(j)}$
 - $\mathbf{H} = \mathbf{\Theta} \mathbf{\Pi} \mathbf{\Pi}' \mathbf{\Theta}$, where $\mathbf{\Theta} = \text{diag}(\theta_1, \dots, \theta_n)$

19.2 SIMPLE Model (Fan et al., 2022)

In SBM, each $\pi_i \in \{e_1, \dots, e_K\}$ with e_k a one entry vector whose k -th component is one. But what if each node i can belong to K different communities? We generalize π_i to be a compositional vector, and interpret it as community membership profile for node i , then

$$\Pr(\mathbf{X}_{ij} = 1) = \theta_i \theta_j \sum_{k=1}^K \sum_{l=1}^K \pi_i(k) \pi_j(l) p_{kl}$$

and $\mathbf{H} = \mathbf{\Theta} \mathbf{\Pi} \mathbf{\Pi}' \mathbf{\Theta}$. Now, consider a new statistical tests for testing whether any given pair of nodes share the same membership profiles, and providing the associated p -values.

19.2.1 Problem Setting

For an undirected graph $G = (V, E)$ with n nodes, let $\mathbf{X} = \{x_{ij}\} \in \mathbb{R}^{n \times n}$ be the **symmetric** adjacency matrix. Under a probabilistic model, assume x_{ij} is an independent realization from a Bernoulli random variable for all upper triangular entries of random matrix \mathbf{X} . Consider the adjacency matrix with the deterministic-random latent structure

$$\mathbf{X} = \mathbf{H} + \mathbf{W}$$

where

- $\mathbf{H} = \{h_{ij}\} \in \mathbb{R}^{n \times n}$ is the deterministic mean matrix of low rank $K \geq 1$
- $\mathbf{W} = \{w_{ij}\} \in \mathbb{R}^{n \times n}$ is a symmetric random matrix with zero mean and independent entries on and above the diagonal

Assume V is decomposed into K disjoint latent communities

$$C_1, \dots, C_K$$

where each node i is associated with the community membership probability vector

$$\boldsymbol{\pi}_i = (\pi_i(1), \dots, \pi_i(K))' \in \mathbb{R}^K$$

s.t.

$$\Pr(i \in C_k) = \pi_i(k), \quad k = 1, \dots, K$$

here, K is unknown but bounded away from ∞ .

19.2.2 Hypothesis Testing

For any given pair of nodes $i \neq j \in V$, the goal is to infer whether they share the same community identity with quantified uncertainty level based on adjacency matrix \mathbf{X} , the hypothesis is

$$H_0 : \pi_i = \pi_j \quad H_1 : \pi_i \neq \pi_j$$

More explicitly, consider the DCMM (Degree Corrected Mixed Membership) model as the underlying network model, s.t. the probability of a link between nodes i and j can be written as

$$\Pr(\mathbf{X}_{ij} = 1) = \theta_i \theta_j \sum_{k=1}^K \sum_{l=1}^K \pi_i(k) \pi_j(l) p_{kl}$$

and

$$\mathbf{H} = \boldsymbol{\Theta} \boldsymbol{\Pi} \boldsymbol{\Pi}' \boldsymbol{\Theta}$$

in matrix form, where $\boldsymbol{\Pi} = (\pi_1, \dots, \pi_n)' \in \mathbb{R}^{n \times K}$ and $\boldsymbol{\Theta} = \text{diag}(\theta_1, \dots, \theta_n)$. Consider

- No degree homogeneity: $\boldsymbol{\Theta} = \sqrt{\theta} \mathbf{I}_n$, then $\mathbf{H} = \theta \boldsymbol{\Pi} \boldsymbol{\Pi}'$. If we eigen-decompose $\mathbf{H} = \mathbf{V} \mathbf{D} \mathbf{V}'$ where $\mathbf{D} = \text{diag}(d_1, \dots, d_K)$ with $|d_1| \geq |d_2| \geq \dots \geq |d_K| > 0$ is the matrix of all K non-zero eigenvalues and $\mathbf{V} = (v_1, \dots, v_K) \in \mathbb{R}^{n \times K}$ is the eigenvectors.
 - the column space spanned by $\boldsymbol{\Pi}$ is the same as the eigenspace spanned by the top K eigenvectors of matrix \mathbf{H}
 - mean matrix \mathbf{H} is **not** observable: replace it with adjacency matrix \mathbf{X} and conduct eigen-decomposition to get eigenvalues $\hat{d}_1, \dots, \hat{d}_n$ and eigenvectors $\hat{v}_1, \dots, \hat{v}_n$. We assume that

$$|\hat{d}_1| \geq |\hat{d}_2| \geq \dots \geq |\hat{d}_n|$$

and let $\hat{\mathbf{V}} = (\hat{v}_1, \dots, \hat{v}_K) \in \mathbb{R}^{n \times K}$.

Without degree heterogeneity first, consider the case where $\Theta = \sqrt{\theta} \mathbf{I}_n$ and $\mathbb{E}(\mathbf{X}) = \mathbf{H} = \theta \mathbf{\Pi} \mathbf{\Pi}'$. If $\pi_i = \pi_j$, then nodes i and j are exchangeable and $\mathbf{V}(i) = \mathbf{V}(j)$. The test statistic for membership information of node i and j is given as

$$T_{ij} = [\hat{\mathbf{V}}(i) - \hat{\mathbf{V}}(j)]' \Sigma_1^{-1} [\hat{\mathbf{V}}(i) - \hat{\mathbf{V}}(j)]$$

where $\Sigma_1^{-1} = \text{Cov}[(e_i - e_j)' \mathbf{W} \mathbf{V} \mathbf{D}^{-1}]$ is the asymptotic variance of $[\hat{\mathbf{V}}(i) - \hat{\mathbf{V}}(j)]$. The regularity conditions are

C1 $\exists c_0 > 0$ s.t.

$$\min \left\{ \frac{|d_i|}{|d_j|} : 1 \leq i \leq j \leq K, d_i \neq -d_j \right\} \geq 1 + c_0$$

C2 $\exists c_0 \in (0, 1), c_2 \in [0, 1/2), c_1 \in (0, 1 - 2c_2)$ s.t. $\lambda_k(\mathbf{\Pi}' \mathbf{\Pi}) \geq c_0 n$, $\lambda_K(\mathbf{P}) \geq n^{-c_2}$ and $\theta \geq n^{-c_1}$

C3 as $n \rightarrow \infty$, all the eigenvalues of $\theta^{-1} \mathbf{D} \Sigma_1 \mathbf{D}$ are bounded away from 0 and ∞

and the test statistics follow the theorem

Theorem 19.2.1: Test Statistics Distribution

Under Condition **C1** and **C2**, and $\Theta = \sqrt{\theta} \mathbf{I}_n$,

- If **C3** holds too, then under the null

$$H_0 : T_{ij} \xrightarrow{\mathcal{D}} \chi_K^2$$

as $n \rightarrow \infty$, where χ_K^2 is the chi-square distribution with K degrees of freedom

- under the alternative,
 - if $n^{1/2-c_2} \sqrt{\theta} \|\pi_i - \pi_j\| \rightarrow \infty$, then for arbitrarily large constant $C > 0$, we have

$$\Pr(T_{ij} > C) \xrightarrow{n \rightarrow \infty} 1$$

- in addition, if Condition **C3** holds, $c_2 = 0$, $\|\pi_i - \pi_j\| \sim \frac{1}{\sqrt{n\theta}}$, and

$$[\mathbf{V}(i) - \mathbf{V}(j)]' \Sigma_1^{-1} [\mathbf{V}(i) - \mathbf{V}(j)] \rightarrow \mu$$

, then

$$T_{ij} \xrightarrow{\mathcal{D}} \chi_K^2(\mu)$$

as $n \rightarrow \infty$, where $\chi_K^2(\mu)$ is a noncentral chi-square distribution with mean μ and K degrees of freedom.

Under the joint null $H_{0,ij} : \pi_i = \pi_j, \forall 1 \leq i \neq j \leq n$, a uniform version of Thm. 19.2.1 is

$$\lim_{n \rightarrow \infty} \sup_{1 \leq i \neq j \leq n} |\Pr(T_{ij} \leq x) - \Pr(X \leq x)| = 0, \forall x \in \mathbf{R}$$

where $X \sim \chi_K^2$. But the test statistic T_{ij} is not directly applicable since the population parameters K and Σ_1 . For consistent estimators satisfying the following condition

$$\begin{aligned} \Pr(\hat{K} = K) &= 1 - o(1) \\ \theta^{-1} \|\mathbf{D}(\hat{\Sigma}_1 - \Sigma_1) \mathbf{D}\|_2 &= o(1) \end{aligned}$$

then the asymptotic results in Thm. 19.2.1 holds.

With degree heterogeneity Define componentwise ratio

$$Y(i, k) = \frac{\hat{v}_k(i)}{\hat{v}_1(i)}, \quad 1 \leq i < n, 2 \leq k \leq K$$

where $\hat{v}_k(i)$ is the i -th component of k -th eigenvector of \mathbf{X} . Due to the **exchangeability** of nodes i and j , under the null it holds that

$$\frac{v_k(j)}{v_1(j)} = \frac{v_k(i)}{v_1(i)}, \quad 2 \leq k \leq K$$

Denote $\mathbf{Y}_i = (Y(i, 2), \dots, Y(i, K))'$, the new test statistics is proposed as

$$G_{ij} = (\mathbf{Y}_i - \mathbf{Y}_j)' \Sigma_2^{-1} (\mathbf{Y}_i - \mathbf{Y}_j)$$

where Σ_2 is the asymptotic variance of $\mathbf{Y}_i - \mathbf{Y}_j$, which is much harder to derive and estimate. So we need to impose four other conditions in addition to Condition C1-C3:

C4 $\exists c_2 \in [0, 1/2), c_3 \in (0, 1 - 2c_2), c_4 > 0, c_5 \in (0, 1)$ s.t.

$$\lambda_K(\mathbf{P}) \geq n^{-c_2} \quad \min_{1 \leq k \leq K} |\mathcal{N}_k| \geq c_5 n \quad \theta_{\max} \leq c_4 \theta_{\min} \quad \theta_{\min}^2 \geq n^{-c_3}$$

C5 $\mathbf{P} = (p_{kl})$ is positive definite, irreducible and has unit diagonal entries, moreover

$$n \min_{1 \leq k \leq K, t=i,j} \text{Var}(\mathbf{e}_t' \mathbf{W} \mathbf{v}_k) \sim n \theta_{\max}^2 \rightarrow \infty$$

C6 all the eigenvalues of

$$(n \theta_{\max}^2)^{-1} \mathbf{D} \text{Cov}(f) \mathbf{D}$$

are bounded away from 0 and ∞

C7 Let η_1 be the first right singular vector of $\mathbf{P} \mathbf{\Pi}' \Theta^2 \mathbf{\Pi}$, it holds that

$$\min_{1 \leq k \leq K} \eta_1(k) > 0 \quad \frac{\max_{1 \leq k \leq K} \eta_1(k)}{\min_{1 \leq k \leq K} \eta_1(k)} \leq C$$

for some positive C , where $\eta_1(k)$ is the k -th entry of η_1 .

Then we have

Theorem 19.2.2: Test Statistic Distribution with Degree Heterogeneity

Under Condition **C1, C4-C7**, with degree heterogeneity,

- under the null,

$$G_{ij} \xrightarrow{\mathcal{D}} \chi_{K-1}^2$$

- under the alternative with $\lambda_2 \left(\pi_i \pi_i' + \pi_i \pi_j' \right) \gg \frac{1}{n^{1-2c} \theta_{\min}^2}$, for any arbitrarily large constant $C > 0$,

$$\Pr(G_{ij} > C) \xrightarrow{n \rightarrow \infty} 1$$

notice that K and Σ_2 are both unknown, we must have

- for estimator $\hat{\Sigma}_2$ of Σ_2 , we need

$$(n \theta_{\max}^2)^{-1} \|\mathbf{D} (\hat{\Sigma}_2 - \Sigma_2) \mathbf{D}\|_2 = o_p(1)$$

replace Σ_2 with $\hat{\Sigma}_2$

- for K , under Condition **C1**, and $|d_K| \gg \sqrt{\log(n)}\alpha_n$ and $\alpha_n \geq n^{c_5}$ for some positive constant c_5 , a consistent thresholding estimator is defined

$$\hat{K} = |\{d_i : \hat{d}_i^2 > 2.01(\log n)\check{d}_n, i \in [n]\}|$$

where the constant 2.01 can be replaced with any other constant slightly larger than 2, $\check{d}_n = \max_{1 \leq l \leq n} \sum_{j=1}^n \mathbf{X}_{lj}$ is the maximum degree of the network

References

Emmanuel Abbe. Community detection and stochastic block models: recent developments. *The Journal of Machine Learning Research*, 18(1):6446–6531, 2017.