

## 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  $\pi_i$  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  $\infty$ .

### 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 DCM (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  $\infty$

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  $\chi_K^2$  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  $\mu$  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  $\Sigma_1$ . 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  $\Sigma_2$  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  $\infty$

**C7** Let  $\eta_1$  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  $\eta_1$ .

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  $\Sigma_2$  are both unknown, we must have

- for estimator  $\hat{\Sigma}_2$  of  $\Sigma_2$ , we need

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

replace  $\Sigma_2$  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

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

where the constant 2.01 can be replaced with any other constant slightly larger than 2, and

$$\check{d}_n = \max_{1 \leq l \leq n} \sum_{j=1}^n \mathbf{X}_{lj}$$

is the maximum degree of the network. For  $\hat{K}$  to be consistent, we need

- Condition **C1** holds
- $|d_K| \gg \sqrt{\log(n)}\alpha_n$ , where  $\alpha_n \geq n^{c_5}$  for some constant  $c_5 > 0$

### 19.3 Rank Inference via Residual Subsampling

Again, consider  $n \times n$  symmetric random matrix  $\tilde{\mathbf{X}}$  and its decomposition

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

where

- $\mathbf{H} = \mathbb{E}(\tilde{\mathbf{X}})$  with some fixed but unknown rank  $K \ll n$ , it can be eigen-decomposed as

$$\mathbf{H} = \mathbf{V}\mathbf{D}\mathbf{V}'$$

where  $\mathbf{D} = \text{diag}(d_1, \dots, d_K)$  are the non-zero eigenvalues of  $\mathbf{H}$  in decreasing magnitude and  $\mathbf{V} = (\mathbf{v}_1, \dots, \mathbf{v}_K)$  are the corresponding eigenvectors

- $\mathbf{W}$  has bounded and independent entries on and above the diagonals

for a simple case (networks with self loops), when the observed data matrix  $\mathbf{X} = \tilde{\mathbf{X}} = \mathbf{H} + \mathbf{W}$ , then we have

$$\begin{aligned} \frac{\sum_{i=1}^n w_{ii}}{\sqrt{\sum_{i=1}^n \mathbb{E} w_{ii}^2}} &\xrightarrow{d} \mathcal{N}(0, 1) \\ \frac{\sum_{i=1}^n \mathbb{E} w_{ii}^2}{\sum_{i=1}^n w_{ii}^2} &\xrightarrow{p} 1 \end{aligned} \quad \Rightarrow \quad \frac{\sum_{i=1}^n w_{ii}}{\sqrt{\sum_{i=1}^n w_{ii}^2}} \xrightarrow{d} \mathcal{N}(0, 1)$$

Let  $\hat{\mathbf{V}}\hat{\mathbf{D}}\hat{\mathbf{V}}' = \sum_{k=1}^{K_0} \hat{d}_k \hat{\mathbf{v}}_k \hat{\mathbf{v}}_k'$  be an estimate of  $\mathbf{H}$  with rank  $K = K_0$ , then

$$\hat{\mathbf{W}} = (\hat{w}_{ij}) = \mathbf{X} -$$

## References

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