Mixed Membership Stochastic Blockmodels

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Overview

1. Review
2. Variational Bayes: General Theory
3. Variational Bayes for the MMSB
4. Conclusion and next steps
5. Issues

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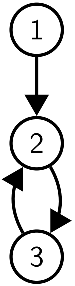
Network theory: notation

- Individuals $p, q \in \{1, \ldots, N\}$.
- We observe relations/interactions $R(p, q)$ on *pairs* of individuals.
- Here we assume $R(p, q) \in \{0, 1\}$, $R(p, p) = 0$, but do not assume $R(p, q) = R(q, p)$ (we deal with *directed* networks).

Network theory: data representations

p	q	R(p,q)
1	2	1
2	3	1
3	2	1

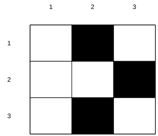
Table



Graph

$$\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

Adjacency matrix i, j element is $R(i, j)$

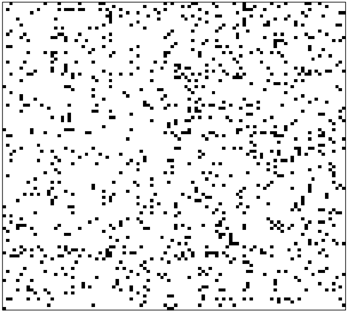


Adjacency matrix, black=1, white=0

The Problem: Scientific Motivation

- We believe the relations are a function of unobserved groupings among the individuals.
- We want to recover the groups so we can a) predict new relations or b) interpret the existing network structure.
- Example: Monk network.

The Problem: Pictures



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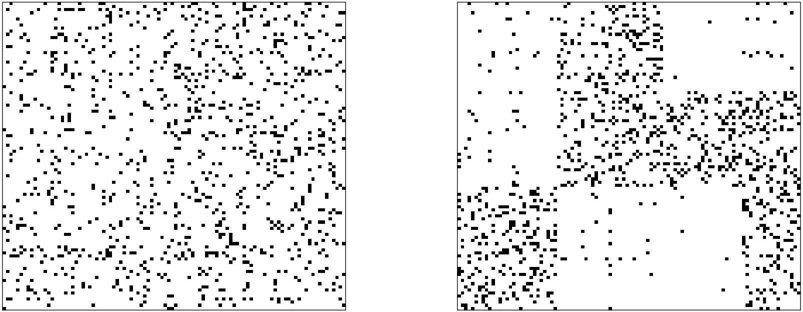


Figure: Two visualizations of the same binary adjacency matrix. Each filled-in square represents a directed edge. Left: ordered randomly. Right: ordered by group membership.

Brief blockmodel history

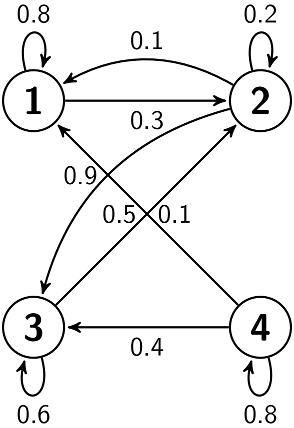
- 1975: CONCOR developed by Harrison White and colleagues
- 1983: Holland, Laskey & Leinhardt introduce *stochastic* blockmodel for blocks known *a priori*.
- 1987: Wasserman & Anderson extend to *a posteriori* estimation.
- 2004: Kemp, Griffiths & Tenenbaum allow unknown and unlimited number of blocks in the Infinite Relational Model.

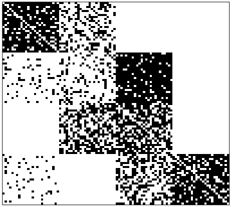
Infinite Relational Model

- Observe binary relations $R(p, q)$ between nodes $p, q \in \{1, \ldots, N\}$.
- Each node p is a member of exactly one block of K total blocks, $K \leq N$ unknown. Let z_p be an indicator vector of block membership for node p, i.e. $z_p = (0, 1, 0)$.
- B is a $K \times K$ matrix of block relationships. If p is in block g and q is in block h then the probability of observing an interaction from node p to node q is B_{gh}.
- $R(p, q) \sim \text{Bernoulli}(z_p^T B z_q)$. 这个表示好！
- For example, if p is in block 3 and q is in block 2 then $P(R(p, q) = 1) = B_{32}$.

Block structure

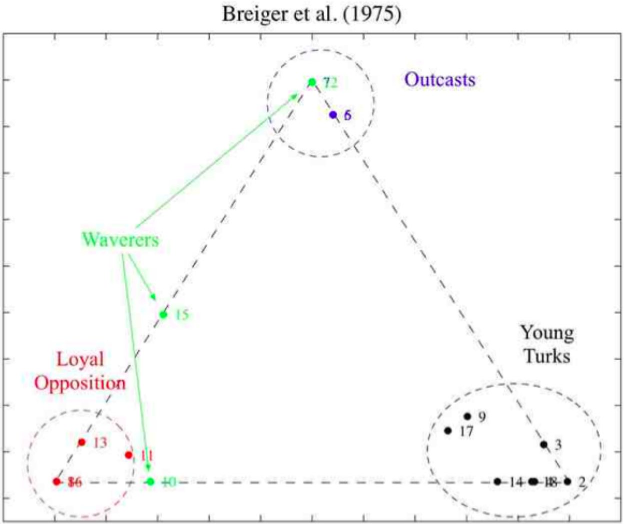
$$\begin{pmatrix} .8 & .3 & 0 & 0 \\ .1 & .2 & .9 & 0 \\ 0 & .5 & .6 & 0 \\ .1 & 0 & .4 & .8 \end{pmatrix}$$





The Mixed Membership Stochastic Blockmodel

- Previous models assume each node is assumed to belong to exactly one latent block - e.g. $z_p = (0, 1, 0, 0)$.
- Instead, in the MMB we assume each node has a distribution π_p over the latent blocks.
- For each interaction from p to q, both p and q draw a particular block to be a part of for the interaction: $z_{p \to q} \sim \text{Discrete}(\pi_p)$, $z_{p \leftarrow q} \sim \text{Discrete}(\pi_q)$.
- Then $R(p, q) \sim \text{Bernoulli}(z_{p \to q}^T B z_{p \leftarrow q})$.
- K chosen by BIC.



1 Ambrose
2 Boniface
3 Mark
4 Winfrid
5 Elias
6 Basil
7 Simplicius
8 Berthold
9 John Bosco
10 Victor
11 Bonaventure
12 Amand
13 Louis
14 Albert
15 Ramuald
16 Peter
17 Gregory
18 Hugh

Overview

Estimation Basics

- Strategy: treat $\{\pi, Z_{\rightarrow}, Z_{\leftarrow}\} \equiv \theta$ as random latent variables and obtain posterior distribution. Treat $\{\alpha, B\} \equiv \beta$ as fixed parameters to estimate via Empirical Bayes.
- The typical approach in this setting is to use the EM algorithm, which involves calculating the posterior distribution $p(\theta | Y, \beta)$.

和SBM对一下

Posterior Calculation

- Great! Write down the form of the posterior $p(\theta|Y,\beta)$:

$$\frac{p(Y|\theta,\beta)p(\theta|\beta)}{p(Y|\beta)}.$$

- The denominator requires calculating the integral

$$\int_{\Pi}\sum_{\Omega}\prod_{p,q}[P(Y(p,q)|z_{p\to q},z_{p\leftarrow q},B)p(z_{p\to q}|\pi_p)p(z_{p\leftarrow q}|\pi_q)]$$
$$\prod_{p}p(\pi_p|\alpha)d\pi_{1:N}$$

- No closed form solution

Variational Bayes

- Main idea: write down a simple parametric form $q(\theta|\Delta)$ for the posterior distribution that depends on free variational parameters Δ.
- At each E-step, minimize the KL divergence between q and the true posterior in terms of the free variational parameters.

$$
\begin{aligned}
K(q,p) &= \mathbb{E}_q\left[\log \frac{q(\theta|\Delta)}{p(\theta|Y,\beta)}\right] \\
&= \mathbb{E}_q\left[\log q(\theta|\Delta)\right] - \mathbb{E}_q\left[\log p(\theta|Y,\beta)\right] \\
&= \mathbb{E}_q\left[\log q(\theta|\Delta)\right] - \mathbb{E}_q\left[\log \frac{p(\theta,Y|\beta)}{p(Y|\beta)}\right] \\
&= \mathbb{E}_q\left[\log q(\theta|\Delta)\right] - \mathbb{E}_q\left[\log p(\theta,Y|\beta)\right] + \log p(Y|\beta).
\end{aligned}
$$

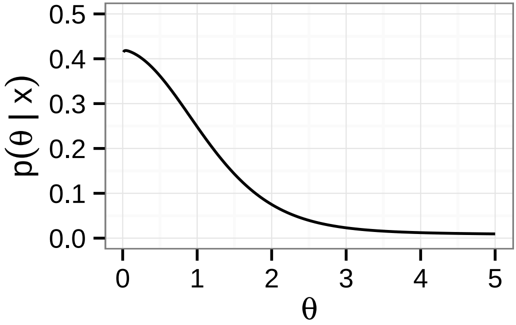
This is equivalent to maximizing the *evidence lower bound* or ELBO

这就是之前的J

$$
\mathcal{L}(\Delta|Y,\beta) = \mathbb{E}_q\left[\log p(\theta,Y|\beta)\right] - \mathbb{E}_q\left[\log q(\theta|\Delta)\right].
$$

Variational Bayes: Example

Suppose we have a complicated posterior distribution p (the one below is a mix of lognormal and t - yuck). We use a variational posterior Gamma(α, β). We minimize the KL divergence between the true and variational posteriors in terms of α and β to get an approximate posterior.



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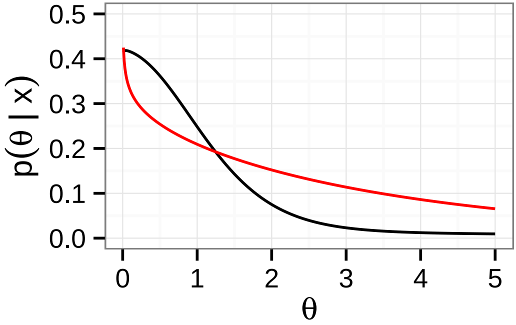

Variational Bayes: Mean-Field Approximation

- How do we know what sort of variational posterior q is easy to work with?
- Most popular strategy is called the mean field approximation: assume q factorizes into a term for each latent variable:

$$q(\theta_1, \ldots, \theta_r | \Delta) = \prod_{i=1}^{r} q_i(\theta_i | \Delta_i).$$

  The optimal form for q_i can be derived from the calculations of variations (hence the name variational inference).
- To minimize the KL divergence (maximize the ELBO) between p and and q, we use coordinate descent over the Δ_i.

Variational EM algorithm

1. Initialize $\beta^{(0)}$, $\Delta^{(0)}$.
2. E-step: Find the $\Delta_{1:r}^{(j)}$ that maximizes $\mathcal{L}(\Delta, \beta^{(j-1)})$ via coordinate ascent:
   (i) For $i = 1, \ldots, r$, maximize $\mathcal{L}(\Delta^{(jk)}, \beta^{(j-1)})$ with respect to Δ_i.
   (ii) If $\|\Delta^{(jk)} - \Delta^{(j(k+1))}\| > \epsilon$ has not converged, return to (i)
3. M-step: Find the $\beta^{(j)}$ that maximizes $\mathcal{L}(\Delta^{(j)}, \beta)$.
4. If $\|\Delta^{(j)} - \Delta^{(j-1)}\| > \epsilon$ or $\|\beta^{(j)} - \beta^{(j-1)}\| > \epsilon$, return to 2.

Overview

Mean-field approximation

- Recall $\theta = \{\pi_{1:N}, Z_{\rightarrow}, Z_{\leftarrow}\}$
- Recall the model distribution for θ:
  - $\pi_p \sim \text{Dirichlet}(\alpha)$
  - $z_{p\rightarrow q} \sim \text{Discrete}(\pi_p)$
  - $z_{p\leftarrow q} \sim \text{Discrete}(\pi_q)$
- Assume the posterior factors as:
  - $\pi_p \sim \text{Dirichlet}(\gamma_p)$
  - $z_{p\rightarrow q} \sim \text{Discrete}(\phi_{p\rightarrow q})$
  - $z_{p\leftarrow q} \sim \text{Discrete}(\phi_{p\leftarrow q})$
- Variation parameters $\Delta = \{\gamma_{1:N}, \Phi_{\rightarrow}, \Phi_{\leftarrow}\}$
- Full approximate posterior:

$$q(\pi_{1:N}, Z_{\rightarrow}, Z_{\leftarrow} | \gamma_p, \Phi_{\rightarrow}, \Phi_{\leftarrow}) = \prod_p q_1(\pi_p|\gamma_p) \prod_{p,q} q_2(z_{p\rightarrow q}|\phi_{p\rightarrow q}) q_2(z_{p\leftarrow q}|\phi_{p\leftarrow q}).$$

Parameter updates

- Now we have to calculate the ELBO

$$
\begin{aligned}
\mathcal{L}(\Delta|Y,\beta) &= \mathbb{E}_q\left[\log p(\theta, Y|\beta)\right] - \mathbb{E}_q\left[\log q(\theta|\Delta)\right] \\
&= \mathbb{E}_q\left[\log p(\pi_{1:N}, Z_{\rightarrow}, Z_{\leftarrow}, Y|\alpha, B)\right] \\
&\qquad - \mathbb{E}_q\left[\log q(\pi_{1:N}, Z_{\rightarrow}, Z_{\leftarrow}|\gamma_{1:N}, \Phi_{\rightarrow}, \Phi_{\leftarrow})\right] \\
&= \cdots \\
&= \mathcal{L}(\gamma_{1:N}, \Phi_{\rightarrow}, \Phi_{\leftarrow}|Y, \alpha, B)
\end{aligned}
$$

(appendix calculations)

- Then differentiate with respect to γ_i, $\phi_{p\rightarrow q}, \phi_{p\leftarrow q}$, α_i, $B(g,h)$, set to 0, and solve.

这。。

Parameter updates

- Get closed form updates:

$$\hat{\phi}_{p\to q,g} \propto e^{\psi(\gamma_{p,g})-\psi(\Sigma_j \gamma_{p,j})} \prod_h \left(B(g,h)^{Y(p,q)} (1-B(g,h))^{1-Y(p,q)} \right)^{\phi_{p\leftarrow q}}$$

$$\hat{\phi}_{p\leftarrow q,h} \propto e^{\psi(\gamma_{q,h})-\psi(\Sigma_j \gamma_{q,j})} \prod_g \left(B(g,h)^{Y(p,q)} (1-B(g,h))^{1-Y(p,q)} \right)^{\phi_{p\to q}}$$

$$\hat{\gamma}_{p,k} = \alpha_k + \sum_q \phi_{p\to q,k} + \sum_q \phi_{q\leftarrow p,k}$$

$$\hat{B}(g,h) = \frac{\sum_{p,q} \phi_{p\to q,g}\phi_{p\leftarrow q,h} Y(p,q)}{\sum_{p,q} \phi_{p\to q,g}\phi_{p\leftarrow q,h}}$$

- No closed form solution for α, so we use a Newton-Raphson algorithm to find maximum:

$$\alpha^{(t+1)} = \alpha^{(t)} - (H_\alpha(\mathcal{L}(\alpha^{(t)})))^{-1}\nabla_\alpha L(\alpha^{(t)})$$

where $\nabla_\alpha L(\alpha^{(t)})$ is the gradient (vector of first derivatives) of the ELBO $\mathcal{L}$ with respect to α and $H_\alpha(\mathcal{L}(\alpha^{(t)}))$ is the hessian (matrix of second derivatives) of the $\mathcal{L}$ with respect to α:

$$\frac{\partial}{\partial \alpha_k}\mathcal{L} = N\left[\psi(\Sigma_j \alpha_j) - \psi(\alpha_k)\right] + \sum_p (\psi(\gamma_{p,k}) - \psi(\Sigma_j \gamma_{p,j}))$$

$$\frac{\partial^2}{\partial \alpha_k \partial \alpha_l}\mathcal{L} = N\left[\psi'(\Sigma_j \alpha_j) - \psi'(\alpha_k)\mathbf{1}_{k=l}\right]$$

"Naive" algorithm for the MMSB

1. Initialize $B^{(0)}, \alpha^{(0)}, \gamma_{1:N}^{(0)}, \Phi_{\rightarrow}^{(0)}, \Phi_{\leftarrow}^{(0)}$.
2. E-step: Find the $\gamma_{1:N}^{(j)}, \Phi_{\rightarrow}^{(j)}, \Phi_{\leftarrow}^{(j)}$ that maximizes $\mathcal{L}(\cdot, \alpha^{(j-1)}, B^{(j-1)})$ via coordinate ascent:
   (i) Update $\gamma_i^{(j)}$ for $i = 1, \ldots, N$
   (ii) Update $\phi_{p\rightarrow q}, \phi_{p\leftarrow q}$ for all p, q
   (iii) Until convergence
3. M-step: Update $B^{(j)}, \alpha^{(j)}$.
4. Until convergence.

"Nested" algorithm for the MMSB

1. Initialize $B^{(0)}, \alpha^{(0)}, \gamma_{1:N}^{(0)}, \Phi_{\rightarrow}^{(0)}, \Phi_{\leftarrow}^{(0)}$.
2. E-step:
   (a) for each p, q:
      (i) Update $\phi_{p\rightarrow q}, \phi_{p\leftarrow q}$ for all p, q
      (ii) Update γ_p, γ_q
      (iii) Update B.
   (b) Until convergence
3. M-step: Update $\alpha^{(j)}$.
4. Until convergence.

Overview

Conclusion and next steps

- Variational inference: approximate the posterior with an easier closed-form posterior; make the approximation as good as possible
- Pros: scales very well, get an exact posterior rather than samples. Cons: Posterior is approximate, and we don't know how good (or bad) the approximation is.
- Next steps: apply to data, simulations

Overview

Sparsity parameter

- The authors introduce a sparsity parameter ρ
- Instead of $Y(p,q) \sim z_{p\to q}^T B z_{p\leftarrow q}$, set $Y(p,q) \sim z_{p\to q}^T (1-\rho) B z_{p\leftarrow q}$.
- Identifiability?