

1 A binary child given a binary parent

Let X and Y be two binary variables. The log-conditional probability of the child-node X given its parent-node Y is expressed as follows:

$$\begin{aligned}\ln p(X|Y) &= I(X=0)I(Y=0) \ln p_{x|y} + I(X=1)I(Y=0) \ln p_{\bar{x}|y} \\ &\quad + I(X=0)I(Y=1) \ln p_{x|\bar{y}} + I(X=1)I(Y=1) \ln p_{\bar{x}|\bar{y}}\end{aligned}$$

This conditional probability can be expressed in different exponential forms as follows:

- **First form:**

$$\begin{aligned}\ln p(X | Y) &= \theta^T s(X, Y) - A(\theta) \\ &= \begin{pmatrix} \ln p_{x|y} \\ \ln p_{\bar{x}|y} \\ \ln p_{x|\bar{y}} \\ \ln p_{\bar{x}|\bar{y}} \end{pmatrix}^T \begin{pmatrix} I(X=0)I(Y=0) \\ I(X=1)I(Y=0) \\ I(X=0)I(Y=1) \\ I(X=1)I(Y=1) \end{pmatrix} - 0 \\ &= \begin{pmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{pmatrix}^T \begin{pmatrix} I(X=0)I(Y=0) \\ I(X=1)I(Y=0) \\ I(X=0)I(Y=1) \\ I(X=1)I(Y=1) \end{pmatrix} - 0\end{aligned}$$

- **Second form:**

$$\begin{aligned}\ln p(X | Y) &= \theta(Y)^T s(X) - A(Y) \\ &= \begin{pmatrix} I(Y=0) \ln p_{x|y} + I(Y=1) \ln p_{x|\bar{y}} \\ I(Y=0) \ln p_{\bar{x}|y} + I(Y=1) \ln p_{\bar{x}|\bar{y}} \end{pmatrix}^T \begin{pmatrix} I(X=0) \\ I(X=1) \end{pmatrix} - 0 \\ &= \begin{pmatrix} m_0^Y \cdot \theta_0 + m_1^Y \cdot \theta_2 \\ m_0^Y \cdot \theta_1 + m_1^Y \cdot \theta_3 \end{pmatrix}^T \begin{pmatrix} I(X=0) \\ I(X=1) \end{pmatrix} - 0\end{aligned}$$

- **Third form:**

$$\begin{aligned}\ln p(X | Y) &= \theta(X)^T s(Y) - A(X) \\ &= \begin{pmatrix} I(X=0) \ln p_{x|y} + I(X=1) \ln p_{\bar{x}|y} \\ I(X=0) \ln p_{x|\bar{y}} + I(X=1) \ln p_{\bar{x}|\bar{y}} \end{pmatrix}^T \begin{pmatrix} I(Y=0) \\ I(Y=1) \end{pmatrix} - 0 \\ &= \begin{pmatrix} m_0^X \cdot \theta_0 + m_1^X \cdot \theta_1 \\ m_0^X \cdot \theta_2 + m_1^X \cdot \theta_3 \end{pmatrix}^T \begin{pmatrix} I(Y=0) \\ I(Y=1) \end{pmatrix} - 0\end{aligned}$$

2 A multinomial child given a set of multinomial parents

Let X be a multinomial variable with k possible values such that $k \geq 2$, and let $\mathbf{Y} = \{Y_1, \dots, Y_n\}$ denote the set of parents of X , such that all of them are multinomial. Each parent Y_i , $1 \leq i \leq n$, has r_i possible values or states such that $r_i \geq 2$. A parental configuration for the child-node X is then a set of n elements $\{Y_1 = y_1^v, \dots, Y_i = y_i^v, \dots, Y_n = y_n^v\}$ such that y_i^v denotes a potential value of variable Y_i such that $1 \leq v \leq r_i$. Let $q = r_1 \times \dots \times r_n$ denote the total number of parental configurations, and let \mathbf{y}^l denote the l^{th} parental configuration such that $1 \leq l \leq q$.

The log-conditional probability of the child-node X given its parent-nodes \mathbf{Y} can be expressed as follows:

$$\ln p(X | \mathbf{Y}) = \sum_{j=1}^k \sum_{l=1}^q I(X = x^j) I(\mathbf{Y} = \mathbf{y}^l) \ln p_{x^j | \mathbf{y}^l}$$

Similarly the above log-conditional probability can be expressed in the following exponential forms:

- **First form:**

$$\ln p(X | \mathbf{Y}) = \theta^T s(X, \mathbf{Y}) - A(\theta)$$

$$\begin{aligned} &= \begin{pmatrix} \ln p_{x^1 | \mathbf{y}^1} \\ \vdots \\ \ln p_{x^1 | \mathbf{y}^q} \\ \vdots \\ \ln p_{x^k | \mathbf{y}^1} \\ \vdots \\ \ln p_{x^k | \mathbf{y}^q} \end{pmatrix}^T \begin{pmatrix} I(X = x^1) I(\mathbf{Y} = \mathbf{y}^1) \\ \vdots \\ I(X = x^1) I(\mathbf{Y} = \mathbf{y}^q) \\ \vdots \\ I(X = x^k) I(\mathbf{Y} = \mathbf{y}^1) \\ \vdots \\ I(X = x^k) I(\mathbf{Y} = \mathbf{y}^q) \end{pmatrix} - 0 \\ &= \begin{pmatrix} \theta_{11} \\ \vdots \\ \theta_{1q} \\ \vdots \\ \theta_{k1} \\ \vdots \\ \theta_{kq} \end{pmatrix}^T \begin{pmatrix} I(X = x^1) I(\mathbf{Y} = \mathbf{y}^1) \\ \vdots \\ I(X = x^1) I(\mathbf{Y} = \mathbf{y}^q) \\ \vdots \\ I(X = x^k) I(\mathbf{Y} = \mathbf{y}^1) \\ \vdots \\ I(X = x^k) I(\mathbf{Y} = \mathbf{y}^q) \end{pmatrix} - 0 \end{aligned}$$

- **Second form:**

$$\begin{aligned}
\ln p(X \mid \mathbf{Y}) &= \theta(\mathbf{Y})^T s(X) - A(\mathbf{Y}) \\
&= \begin{pmatrix} I(\mathbf{Y} = \mathbf{y}^1) \ln p_{x^1|\mathbf{y}^1} + \dots + I(\mathbf{Y} = \mathbf{y}^q) \ln p_{x^1|\mathbf{y}^q} \\ \vdots \\ I(\mathbf{Y} = \mathbf{y}^1) \ln p_{x^k|\mathbf{y}^1} + \dots + I(\mathbf{Y} = \mathbf{y}^q) \ln p_{x^k|\mathbf{y}^q} \end{pmatrix}^T \begin{pmatrix} I(X = x^1) \\ \vdots \\ I(X = x^k) \end{pmatrix} - 0 \\
&= \begin{pmatrix} \mathbf{m}_1^{\mathbf{Y}} \cdot \theta_{11} + m_q^{\mathbf{Y}} \cdot \theta_{1q} \\ \vdots \\ \mathbf{m}_1^{\mathbf{Y}} \cdot \theta_{k1} + m_q^{\mathbf{Y}} \cdot \theta_{kq} \end{pmatrix}^T \begin{pmatrix} I(X = x^1) \\ \vdots \\ I(X = x^k) \end{pmatrix} - 0
\end{aligned}$$

such that $\mathbf{m}_1^{\mathbf{Y}} = \prod_{i=1}^n I(Y_i = y_i^1) = \prod_{i=1}^n m_1^{Y_i}$ denotes the expected sufficient statistics for the first parental configuration, and $\mathbf{m}_q^{\mathbf{Y}} = \prod_{i=1}^n I(Y_i = y_i^{r_i}) = \prod_{i=1}^n m_{r_i}^{Y_i}$ denotes the expected sufficient statistics for the last parental configuration.

- **Third form:**

$$\begin{aligned}
\ln p(X \mid \mathbf{Y}) &= \theta(X)^T s(\mathbf{Y}) - A(X) \\
&= \begin{pmatrix} I(X = x^1) \ln p_{x^1|\mathbf{y}^1} + \dots + I(X = x^k) \ln p_{x^k|\mathbf{y}^1} \\ \vdots \\ I(X = x^1) \ln p_{x^1|\mathbf{y}^q} + \dots + I(X = x^k) \ln p_{x^k|\mathbf{y}^q} \end{pmatrix}^T \begin{pmatrix} I(\mathbf{Y} = \mathbf{y}^1) \\ \vdots \\ I(\mathbf{Y} = \mathbf{y}^q) \end{pmatrix} - 0 \\
&= \begin{pmatrix} m_1^X \cdot \theta_{11} + \dots + m_k^X \cdot \theta_{k1} \\ \vdots \\ m_1^X \cdot \theta_{1q} + \dots + m_k^X \cdot \theta_{kq} \end{pmatrix}^T \begin{pmatrix} I(\mathbf{Y} = \mathbf{y}^1) \\ \vdots \\ I(\mathbf{Y} = \mathbf{y}^q) \end{pmatrix} - 0
\end{aligned}$$

$$\begin{aligned}
\ln p(X \mid \mathbf{Y}) &= \theta(X, \mathbf{Y}')^T s(Y_i) - A(X) \quad \text{such that } \mathbf{Y}' = \mathbf{Y} \setminus Y_i \\
&= \begin{pmatrix} m_1^X I(\mathbf{Y}' = \mathbf{y}'^1) \ln p_{x^1|\mathbf{y}'^1} + \dots + m_k^X I(\mathbf{Y}' = \mathbf{y}'^1) \ln p_{x^k|\mathbf{y}'^1} \\ \vdots \\ m_1^X I(\mathbf{Y}' = \mathbf{y}'^{q'}) \ln p_{x^1|\mathbf{y}'^{q'}} + \dots + m_k^X I(\mathbf{Y}' = \mathbf{y}'^{q'}) \ln p_{x^k|\mathbf{y}'^{q'}} \end{pmatrix}^T \begin{pmatrix} I(Y_i = y_i^1) \\ \vdots \\ I(Y_i = y_i^{r_i}) \end{pmatrix} - 0 \\
&= \begin{pmatrix} m_1^X \cdot \mathbf{m}_1^{\mathbf{Y}'} \cdot \theta'_{11} + \dots + m_k^X \cdot \mathbf{m}_1^{\mathbf{Y}'} \cdot \theta'_{k1} \\ \vdots \\ m_1^X \cdot \mathbf{m}_{q'}^{\mathbf{Y}'} \cdot \theta'_{1q'} + \dots + m_k^X \cdot \mathbf{m}_{q'}^{\mathbf{Y}'} \cdot \theta'_{kq'} \end{pmatrix}^T \begin{pmatrix} I(Y_i = y_i^1) \\ \vdots \\ I(Y_i = y_i^{r_i}) \end{pmatrix} - 0
\end{aligned}$$

where $\mathbf{m}_1^{\mathbf{Y}'} = I(\mathbf{Y}' = \mathbf{y}'^1) = I(Y_1 = y_1^1) \cdot \dots \cdot I(Y_{i-1} = y_{i-1}^1) \cdot I(Y_{i+1} = y_{i+1}^1) \cdot \dots \cdot I(Y_n = y_n^1)$ denotes the expected sufficient statistics for the first configuration of the parent set $\mathbf{Y}' = \mathbf{Y} \setminus Y_i$, and $\mathbf{m}_{q'}^{\mathbf{Y}'} = I(\mathbf{Y}' = \mathbf{y}'^{q'}) = I(Y_1 = y_1^{q'}) \cdot \dots \cdot I(Y_{i-1} = y_{i-1}^{q'}) \cdot I(Y_{i+1} = y_{i+1}^{q'}) \cdot \dots \cdot I(Y_n = y_n^{q'})$ denotes the expected sufficient statistics for the last configuration of the parent set \mathbf{Y}' , with $q' = q/r_i$ denotes the total number of configurations of the parent set \mathbf{Y}' .

3 A normal child given a set of normal parents

Let X be a normal variable and $\mathbf{Y} = \{Y_1, \dots, Y_n\}$ denote the set of parents of X , such that all of them are normal.

The log-conditional probability of X given its parents \mathbf{Y} can be expressed as follows:

$$\ln p(X|Y_1, \dots, Y_n) = \ln \left(\frac{1}{\sigma \sqrt{2(\beta_0 + \sum_i^n \beta_i Y_i)}} e^{-\frac{(y - (\beta_0 + \sum_i^n \beta_i Y_i))^2}{2\sigma^2}} \right)$$

Similarly the above log-conditional probability can be expressed in the following exponential forms:

- **First form - Joint suff. stat. (Maxim. Likelihood):**

$$\ln p(X | \mathbf{Y}) = \theta^T s(X, \mathbf{Y}) - A(\theta) + h(\mathbf{Y})$$

$$= \begin{pmatrix} \frac{-1}{2\sigma^2} & = & \theta_{-1} \\ \frac{-\beta_1^2}{2\sigma^2} & = & \theta_{1^2} \\ \vdots & & \\ \frac{-\beta_n^2}{2\sigma^2} & = & \theta_{n^2} \\ \frac{\beta_0}{\sigma^2} & = & \theta_0 \\ \frac{\beta_1}{\sigma^2} & = & \theta_1 \\ \vdots & & \\ \frac{\beta_n}{\sigma^2} & = & \theta_n \\ \frac{-\beta_0\beta_1}{\sigma^2} & = & \theta_{01} \\ \vdots & & \\ \frac{-\beta_0\beta_n}{\sigma^2} & = & \theta_{0n} \\ \frac{-\beta_1\beta_2}{\sigma^2} & = & \theta_{12} \\ \vdots & & \\ \frac{-\beta_1\beta_n}{\sigma^2} & = & \theta_{1n} \\ \vdots & & \\ \frac{-\beta_{n-1}\beta_n}{\sigma^2} & = & \theta_{n-1n} \end{pmatrix}^T \begin{pmatrix} X^2 & = & m_{X^2} \\ Y_1^2 & = & m_{Y_1^2} \\ \vdots & & \\ Y_n^2 & = & m_{Y_n^2} \\ X & = & m_X \\ XY_1 & = & m_{XY_1} \\ \vdots & & \\ XY_n & = & m_{XY_n} \\ Y_1 & = & m_{Y_1} \\ \vdots & & \\ Y_n & = & m_{Y_n} \\ Y_1 Y_2 & = & m_{Y_1 Y_2} \\ \vdots & & \\ Y_1 Y_n & = & m_{Y_1 Y_n} \\ \vdots & & \\ Y_{n-1} Y_n & = & m_{Y_{n-1} Y_n} \end{pmatrix} - \left(\frac{\beta_0^2}{2\sigma^2} + \ln \sigma \right) + \frac{1}{\ln \sqrt{2\mu_{X|Y}}}$$

where $\mu_{X|Y} = \beta_0 + \sum_i^n \beta_i Y_i$

- **From moment to natural parameters: (matrix representation)**

$$\begin{aligned}
\ln p(X | \mathbf{Y}) &= \theta^T s(X, \mathbf{Y}) - A(\theta) + h(\mathbf{Y}) \\
&= \begin{pmatrix} \frac{-1}{2\sigma^2} &= \theta_{-1} \\ \frac{\beta}{\sigma^2} &= \theta_\beta \\ \frac{-\beta^T \beta}{2\sigma^2} &= \theta_{\beta^T \beta} \end{pmatrix} \begin{pmatrix} XX^T &= \mathbb{E}(XX^T) \\ Y'X &= \mathbb{E}(YX) \\ Y'Y'^T &= \mathbb{E}(YY'^T) \end{pmatrix} - (\ln \sigma) + \frac{1}{\ln \sqrt{2\mu_{X|Y}}}
\end{aligned}$$

where

$$X = \begin{pmatrix} X_1 \\ \vdots \\ X_r \end{pmatrix}$$

$$Y = \begin{pmatrix} Y_1 \\ \vdots \\ Y_n \end{pmatrix}$$

$$Y'Y'^T = \begin{pmatrix} 1 \\ Y_1 \\ \vdots \\ Y_n \end{pmatrix} \begin{pmatrix} 1 & Y_1 & \cdots & Y_n \end{pmatrix} = \begin{pmatrix} 1 & Y_1 & \cdots & Y_n \\ Y_1 & Y_1 Y_1 & \cdots & Y_1 Y_n \\ Y_2 & Y_2 Y_1 & \cdots & Y_2 Y_n \\ \vdots & \vdots & \ddots & \vdots \\ Y_n & Y_n Y_1 & \cdots & Y_n Y_n \end{pmatrix}$$

$$XX^T = \begin{pmatrix} X_1 \\ \vdots \\ X_r \end{pmatrix} \begin{pmatrix} X_1 & \cdots & X_r \end{pmatrix} = \begin{pmatrix} X_1 X_1 & \cdots & X_1 X_r \\ X_2 X_1 & \cdots & X_2 X_r \\ \vdots & \ddots & \vdots \\ X_r X_1 & \cdots & X_r X_r \end{pmatrix}$$

$$Y'X^T = \begin{pmatrix} Y_1 \\ \vdots \\ Y_n \end{pmatrix} \begin{pmatrix} X_1 & \cdots & X_r \end{pmatrix} = \begin{pmatrix} X_1 & X_2 & \cdots & X_r \\ Y_1 X_1 & Y_1 X_2 & \cdots & Y_1 X_r \\ \vdots & \vdots & \ddots & \vdots \\ Y_n X_1 & Y_n X_2 & \cdots & Y_n X_r \end{pmatrix}$$

* FIRST STEP:

$$\mu_X = E(X) = E(Y'X)_{[1,r]}$$

$$\mu_Y = E(Y) = E(YY'^T)_{[1,n]}$$

$$\Sigma_{XX} = E(XX^T) - E(X)^2 = E(XX^T) - E(YX)_{[1,r]}^T E(YX)_{[1,r]}$$

$$\Sigma_{YY} = E(YY'^T) - E(Y)^2 = E(YY'^T) - E(YY'^T)_{[n,1]} E(YY'^T)_{[1,n]}$$

$$\Sigma_{XY} = E(YX)^T - E(X) E(Y) = E(YX)^T - E(YX)_{[1,r]} E(YY'^T)_{[n,1]}$$

$$\Sigma_{YX} = E(YX) - E(Y) E(X) = E(YX) - E(YY'^T)_{[n,1]} E(YX)_{[1,r]}$$

* SECOND STEP (Theorem 7.4 in page 253, Koller & Friedman):

$$\begin{aligned}\beta_0 &= \mu_X - \Sigma_{X\mathbf{Y}}\Sigma_{\mathbf{Y}\mathbf{Y}}^{-1}\mu_{\mathbf{Y}} \\ \beta &= \Sigma_{X\mathbf{Y}}\Sigma_{\mathbf{Y}\mathbf{Y}}^{-1} \\ \sigma^2 &= \Sigma_{XX} - \Sigma_{X\mathbf{Y}}\Sigma_{\mathbf{Y}\mathbf{Y}}^{-1}\Sigma_{\mathbf{Y}X}\end{aligned}$$

All natural parameters θ can now be calculated considering these equations.

– **From natural to moment parameters:** Via inference.

• **Second form:**

$$\begin{aligned}\ln p(X \mid \mathbf{Y}) &= \theta(\mathbf{Y})^T s(X) - A(\theta(\mathbf{Y})) + h(\mathbf{Y}) \\ &= \left(\frac{\mu_{X|Y}}{\frac{\sigma^2}{2\sigma^2}} \right)^T \begin{pmatrix} X \\ X^2 \end{pmatrix} - \left(\frac{\mu_{X|Y}^2}{2\sigma^2} + \ln \sigma \right) + \ln \frac{1}{\sqrt{2\mu_{X|Y}}} \\ &= \begin{pmatrix} \theta_0 + \sum_i^n \theta_i m^{Y_i} \\ \theta_{-1} \end{pmatrix}^T \begin{pmatrix} X \\ X^2 \end{pmatrix} - \left(\frac{\ln(2\theta_{-1})}{2} - \theta_{-1} \left(\theta_0 + \sum_i^n \theta_i m^{Y_i} \right)^2 \right) \\ &+ \ln \frac{1}{\sqrt{2(\theta_0 + \sum_i^n \theta_i m^{Y_i})}}\end{aligned}$$

• **Third form:**

$$\ln p(X \mid \mathbf{Y}) = \theta(X)^T s(\mathbf{Y}) - A(\theta(X)) + h(\mathbf{Y})$$

$$\begin{aligned}
&= \begin{pmatrix} -\frac{\beta_1^2}{2\sigma^2} \\ \dots \\ -\frac{\beta_n^2}{2\sigma^2} \\ \frac{\beta_1(X-\beta_0)}{\sigma^2} \\ \dots \\ \frac{\beta_n(X-\beta_0)}{\sigma^2} \\ -\frac{\beta_1\beta_2}{\sigma^2} \\ \dots \\ -\frac{\beta_1\beta_n}{\sigma^2} \\ \dots \\ -\frac{\beta_{n-1}\beta_n}{\sigma^2} \end{pmatrix}^T \begin{pmatrix} Y_1^2 \\ \dots \\ Y_n^2 \\ Y_1 \\ \dots \\ Y_n \\ Y_1Y_2 \\ \dots \\ Y_1Y_n \\ \dots \\ Y_{n-1}Y_n \end{pmatrix} - \left(\frac{(X-\beta_0)^2}{\sigma^2} + \ln \sigma \right) + \frac{1}{\ln \sqrt{2\mu_{X|Y}}} \\
&= \begin{pmatrix} \theta_{1^2} \\ \dots \\ \theta_{n^2} \\ \theta_1 m^X + \theta_{01} \\ \dots \\ \theta_n m^X + \theta_{0n} \\ \theta_{12} \\ \dots \\ \theta_{1n} \\ \dots \\ \theta_{n-1n} \end{pmatrix}^T \begin{pmatrix} Y_1^2 \\ \dots \\ Y_n^2 \\ Y_1 \\ \dots \\ Y_n \\ Y_1Y_2 \\ \dots \\ Y_1Y_n \\ \dots \\ Y_{n-1}Y_n \end{pmatrix} - \left(\frac{X^2 - 2X\beta_0 + \beta_0^2}{\sigma^2} + \ln \sigma \right) + \frac{1}{\ln \sqrt{2\mu_{X|Y}}} \\
&= \begin{pmatrix} \theta_{1^2} \\ \dots \\ \theta_{n^2} \\ \theta_1 m^X + \theta_{01} \\ \dots \\ \theta_n m^X + \theta_{0n} \\ \theta_{12} \\ \dots \\ \theta_{1n} \\ \dots \\ \theta_{n-1n} \end{pmatrix}^T \begin{pmatrix} Y_1^2 \\ \dots \\ Y_n^2 \\ Y_1 \\ \dots \\ Y_n \\ Y_1Y_2 \\ \dots \\ Y_1Y_n \\ \dots \\ Y_{n-1}Y_n \end{pmatrix} - \left((-2\beta_{-1}m^{X^2} - 2m^X\beta_0 - \frac{1}{2}\beta_0^2\beta_{-1}^{-1}) + \frac{\ln(2\theta_{-1})}{2} \right) \\
&+ \ln \frac{1}{\sqrt{2(\theta_0 + \sum_i^n \theta_i m^{Y_i})}}
\end{aligned}$$

Notations

The list below presents a summary of the used notations:

X	Child variable
k	Range of possible values of a multinomial variable X
j	Index over X values, i.e., $1 \geq j \geq k$
Y	One parent variable
\mathbf{Y}	Set of parent variables
n	Number of parent variables
i	Index over parent variables, i.e., $1 \geq i \geq n$
r_i	Range of possible values of a multinomial variable Y_i
q	Total number of configurations of a multinomial parent set \mathbf{Y}
l	Index over the possible parental configuration values, i.e., $1 \geq l \geq q$
\mathbf{y}^l	The l^{th} configuration of a multinomial parent set \mathbf{Y}
θ_{jl}	Equal to $\ln p_{x^j \mathbf{y}^l}$, denoting the log-conditional probability of X in its state j given the l^{th} parent configuration
p	Probability distribution
m	Expected sufficient statistics
s	Sufficient statistics