

Statistical Modeling 2

Exercise 1

January 27, 2017

1 Bayesian inference in simple conjugate families

A

$$p(w \mid x_1, \dots, x_N) \propto p(x_1, \dots, x_N \mid w)p(w) \quad (\text{Bayes rule})$$

$$\propto \prod_{i=1}^N p(x_i \mid w) w^{a-1} (1-w)^{b-1} \quad (\text{independence})$$

$$\begin{aligned} &\propto w^s (1-w)^{N-s} w^{a-1} (1-w)^{b-1} \quad (\text{let } s = \sum_{i=1}^N x_i) \\ &= w^{s+a-1} (1-w)^{N-s+b-1} \\ &\propto \text{Beta}(s+a, N-s+b) \end{aligned}$$

B

Let $f(x_1, x_2) = (y_1, y_2) = (x_1/(x_1 + x_2), x_1 + x_2)$, we have:

$$f^{-1}(y_1, y_2) = (x_1, x_2) = (y_1 y_2, y_2 - y_1 y_2)$$

We then calculate the Jacobian of f^{-1} :

$$\begin{aligned} \partial x_1 / \partial y_1 &= y_2 \\ \partial x_1 / \partial y_2 &= y_1 \\ \partial x_2 / \partial y_1 &= -y_2 \\ \partial x_2 / \partial y_2 &= 1 - y_1 \end{aligned}$$

Therefore,

$$\begin{aligned} |J(f^{-1})| &= \begin{vmatrix} y_2 & y_1 \\ -y_2 & 1 - y_1 \end{vmatrix} \\ &= y_2(1 - y_1) + y_1 y_2 \\ &= y_2 \end{aligned}$$

Let p_X be the joint density of (x_1, x_2) . We have the joint density of y_1 and y_2 :

$$\begin{aligned}
p(y_1, y_2) &= p_X(f^{-1}(y_1, y_2)) |J(f^{-1}(y_1, y_2))| \\
&= \text{Ga}(y_1 y_2; a_1, 1) \text{Ga}(y_2 - y_1 y_2; a_2, 1) y_2 \\
&= \frac{(y_1 y_2)^{a_1-1} \exp(-y_1 y_2)}{\Gamma(a_1)} \frac{((1 - y_1) y_2)^{a_2-1} \exp(y_1 y_2 - y_2)}{\Gamma(a_2)} y_2 \\
&= \frac{y_1^{a_1-1} y_2^{a_1+a_2-1} (1 - y_1)^{a_2-1} \exp(-y_2)}{\Gamma(a_1) \Gamma(a_2)}
\end{aligned}$$

The marginals are:

$$\begin{aligned}
p(y_1) &= \int_0^\infty p(y_1, y_2) dy_2 \\
&= \frac{y_1^{a_1-1} (1 - y_1)^{a_2-1}}{\Gamma(a_1) \Gamma(a_2)} \int_0^\infty y_2^{a_1+a_2-1} \exp(-y_2) dy_2 \\
&= \frac{y_1^{a_1-1} (1 - y_1)^{a_2-1} \Gamma(a_1 + a_2)}{\Gamma(a_1) \Gamma(a_2)}
\end{aligned}$$

and

$$\begin{aligned}
p(y_2) &= \int_0^\infty p(y_1, y_2) dy_1 \\
&= \frac{y_2^{a_1+a_2-1} \exp(-y_2)}{\Gamma(a_1) \Gamma(a_2)} \int_0^\infty y_1^{a_1-1} (1 - y_1)^{a_2-1} dy_1 \\
&= \frac{y_2^{a_1+a_2-1} \exp(-y_2)}{\Gamma(a_1) \Gamma(a_2)} \text{Beta}(a_1, a_2)
\end{aligned}$$

We can simulate a Beta random variable by taking two Gamma random variable as x_1 and x_2 and evaluate y_1 .

C

The posterior is:

$$\begin{aligned}
p(\theta|x_1, \dots, x_N) &\propto p(x_1, \dots, x_N|\theta)p(\theta) \\
&= \prod_{i=1}^N N(x_i; \theta, \sigma^2) N(\theta; m, v) \\
&\propto \prod_{i=1}^N \exp\left(-\frac{(x_i - \theta)^2}{2\sigma^2}\right) \exp\left(-\frac{(\theta - m)^2}{2v}\right) \\
&= \prod_{i=1}^N \exp\left(-\frac{x_i^2 - 2x_i\theta + \theta^2}{2\sigma^2}\right) \exp\left(-\frac{\theta^2 - 2\theta m + m^2}{2v}\right) \\
&= \exp\left(\frac{-\sum_i x_i^2 + 2\sum_i x_i\theta - N\theta^2}{2\sigma^2}\right) \exp\left(\frac{-\theta^2 + 2\theta m - m^2}{2v}\right) \\
&= \exp\left(-\theta^2\left(\frac{N}{2\sigma^2} + \frac{1}{2v}\right) + \theta\left(\frac{\sum_i x_i}{\sigma^2} + \frac{m}{v}\right) - \frac{\sum_i x_i^2}{2\sigma^2} - \frac{m^2}{2v}\right)
\end{aligned}$$

We then complete the square by setting the posterior to:

$$\begin{aligned}
&= \exp\left[-a(\theta^2 - 2b\theta + b^2)\right] \\
&= \exp\left[-a(\theta - b)^2\right] \\
&= \exp\left[-\frac{(\theta - b)^2}{2(1/(2a))}\right]
\end{aligned}$$

We calculate a, b by matching coefficients:

$$\begin{aligned}
a &= \frac{N}{2\sigma^2} + \frac{1}{2v} = \frac{Nv + \sigma^2}{2\sigma^2 v} \\
2ab &= \frac{\sum_i x_i}{\sigma^2} + \frac{m}{v} \\
\implies b &= \frac{v \sum_i x_i + m\sigma^2}{v\sigma^2} \frac{\sigma^2 v}{Nv + \sigma^2} \\
&= \frac{v \sum_i x_i + m\sigma^2}{Nv + \sigma^2}
\end{aligned}$$

The posterior is then:

$$\begin{aligned}
&N(b, 1/(2a)) \\
&= N\left(\frac{v \sum_i x_i + m\sigma^2}{Nv + \sigma^2}, \frac{\sigma^2 v}{Nv + \sigma^2}\right)
\end{aligned}$$

D

$$\begin{aligned}
p(\omega \mid x_1, \dots, x_N) &\propto \prod_{i=1}^N p(x_i \mid \theta, \omega) p(\omega) \\
&\propto \prod_{i=1}^N \omega^{1/2} \exp \left[-\frac{\omega}{2} (x_i - \theta)^2 \right] \frac{b^a}{\Gamma(a)} \omega^{a-1} \exp(-b\omega) \\
&\propto \omega^{N/2+a-1} \exp \left[-\omega \left(b + \frac{\sum_i (x_i - \theta)^2}{2} \right) \right] \\
&\propto \text{Ga} \left(a + \frac{N}{2}, b + \frac{\sum_i (x_i - \theta)^2}{2} \right)
\end{aligned}$$

We have the posterior of the variance:

$$p(\sigma^2 \mid x_1, \dots, x_N) = \text{IG} \left(a + \frac{N}{2}, b + \frac{\sum_i (x_i - \theta)^2}{2} \right)$$

E

The posterior is:

$$\begin{aligned}
p(\theta \mid x_1, \dots, x_N) &\propto p(x_1, \dots, x_N \mid \theta) p(\theta) \\
&= \prod_{i=1}^N \text{N}(x_i; \theta, \sigma_i^2) \text{N}(\theta; m, v) \\
&\propto \prod_{i=1}^N \exp \left(-\frac{(x_i - \theta)^2}{2\sigma_i^2} \right) \exp \left(-\frac{(\theta - m)^2}{2v} \right) \\
&= \exp \left(-\sum_{i=1}^n \frac{(x_i - \theta)^2}{2\sigma_i^2} - \frac{(\theta - m)^2}{2v} \right) \\
&= \exp \left[-\frac{1}{2} \left(\sum_{i=1}^n \frac{(x_i - \theta)^2}{\sigma_i^2} + \frac{(\theta - m)^2}{v} \right) \right] \\
&= \exp \left[-\frac{1}{2} \left(\sum_{i=1}^n \frac{x_i^2}{\sigma_i^2} + \sum_{i=1}^n \frac{-2x_i\theta}{\sigma_i^2} + \sum_{i=1}^n \frac{\theta^2}{\sigma_i^2} + \frac{\theta^2 - 2\theta m + m^2}{v} \right) \right] \\
&= \exp \left\{ -\frac{1}{2} \left[\theta^2 \left(\sum_{i=1}^n \frac{1}{\sigma_i^2} + \frac{1}{v} \right) - 2\theta \left(\sum_{i=1}^n \frac{x_i}{\sigma_i^2} + \frac{m}{v} \right) + \sum_{i=1}^n \frac{x_i^2}{\sigma_i^2} + \frac{m^2}{v} \right] \right\} \\
\text{set } &= \exp \left\{ -\frac{1}{2} [a(\theta^2 - 2\theta b + b^2)] \right\} \\
&= \exp \left\{ -\frac{1}{2} \left[\frac{(\theta - b)^2}{1/a} \right] \right\}
\end{aligned}$$

Matching the coefficients, we have:

$$a = \sum_{i=1}^n \frac{1}{\sigma_i^2} + \frac{1}{v}$$

$$b = \left(\sum_{i=1}^N \frac{x_i}{\sigma_i^2} + \frac{m}{v} \right) / \left(\sum_{i=1}^n \frac{1}{\sigma_i^2} + \frac{1}{v} \right)$$

The posterior is:

$$N(b, 1/a)$$

F

$$\begin{aligned} p(x) &= \int_0^\infty p(x | \sigma^2) p(\sigma^2) d\sigma^2 \\ &= \int_0^\infty p(x | \omega) p(\omega) d\omega \\ &= \int_0^\infty \left(\frac{\omega}{2\pi} \right)^{1/2} \exp\left(-\frac{\omega}{2} x^2\right) \frac{b^a}{\Gamma(a)} \omega^{a-1} \exp(-b\omega) d\omega \\ &= \frac{b^a}{(2\pi)^{1/2} \Gamma(a)} \int_0^\infty \omega^{1/2+a-1} \exp\left(-\omega \left(\frac{x^2}{2} + b\right)\right) d\omega \\ &= \frac{b^a}{(2\pi)^{1/2} \Gamma(a)} \frac{\Gamma(a + 1/2)}{(b + x^2/2)^{a+1/2}} \quad (\text{Gamma integral}) \\ &= \frac{\Gamma(a + 1/2)}{(2\pi b)^{1/2} \Gamma(a) (1 + \frac{x^2}{2b})^{a+1/2}} \end{aligned}$$

Let $\nu = 2a$ and $\lambda = a/b$, we have:

$$p(x) = \frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\nu/2)} \left(\frac{\lambda}{\pi\nu} \right)^{1/2} \left(1 + \frac{\lambda x^2}{2} \right)^{-\frac{\nu+1}{2}}$$

This is the Student t distribution with ν degree of freedom and ‘precision’ λ .

2 The multivariate normal distribution

A

$$\begin{aligned} \text{cov}(x) &= E\{(x - \mu)(x - \mu)^T\} \\ &= E\{xx^T - x\mu^T - \mu x^T + \mu\mu^T\} \\ &= E(xx^T) - E(x)\mu^T - \mu E(x)^T + \mu\mu^T \\ &= E(xx^T) - \mu\mu^T \end{aligned}$$

We have:

$$E(Ax + b) = AE(x) + b = A\mu + b$$

then

$$\begin{aligned} \text{cov}(Ax + b) &= E\{[(Ax + b) - (A\mu + b)][(Ax + b) - (A\mu + b)]^T\} \\ &= E\{(Ax - A\mu)(Ax - A\mu)^T\} \\ &= E\{A(x - \mu)(x - \mu)^T A^T\} \\ &= AE\{(x - \mu)(x - \mu)^T\}A^T \\ &= A\text{cov}(x)A^T \end{aligned}$$

B

$$\begin{aligned} p(z) &= \prod_{i=1}^p p(z_i) \\ &= \frac{1}{(\sqrt{2\pi})^p} \exp\left(-\sum_{i=1}^p \frac{z_i^2}{2}\right) \\ &= \frac{1}{(\sqrt{2\pi})^p} \exp\left(-\frac{z^T z}{2}\right) \end{aligned}$$

The MGF of z is:

$$\begin{aligned} E(\exp(t^T z)) &= E\left[\exp\left(\sum_{i=1}^p t_i z_i\right)\right] \\ &= E\left[\prod_{i=1}^p \exp(t_i z_i)\right] \\ &= \prod_{i=1}^p E[\exp(t_i z_i)] \\ &= \prod_{i=1}^p \exp(t_i^2/2) \\ &= \exp\left[\sum_{i=1}^p t_i^2/2\right] \\ &= \exp(t^T t/2) \end{aligned}$$

C

We need to prove that for all vector a not identically zero, the scalar quantity $z = a^T x$ is normally distributed if and only if

$$E[\exp(t^T x)] = \exp(t^T \mu + t^T \Sigma t/2)$$

(only if) We have that $z = a^T x$ is normally distributed:

$$\text{MGF}_z(s) = E[\exp(sa^T x)] = \exp(ms + vs^2/2)$$

Consider:

D

We have $z \sim N(0, I)$ and $x = Lz + \mu$.

The MGF of x is:

$$E(\exp(t^T x)) = E[\exp(t^T Lz + t^T \mu)]$$

The expectation is with respect to z , $t^T \mu$ is a constant, we then look at:

$$\begin{aligned} E[\exp(t^T Lz)] &= E \left[\exp \left(\sum_{i=1}^p \sum_{j=1}^p t_i L_{ij} z_j \right) \right] \\ &= E \left[\prod_{j=1}^p \exp \left(\sum_{i=1}^p t_i L_{ij} z_j \right) \right] \\ &= \prod_{j=1}^p E \left[\exp \left(\sum_{i=1}^p t_i L_{ij} z_j \right) \right] \quad (\text{independence}) \\ &= \prod_{j=1}^p \text{MGF}_{z_j} \left(\sum_{i=1}^p t_i L_{ij} \right) \\ &= \prod_{j=1}^p \exp \left(\frac{1}{2} (t^T L_j)^2 \right) \\ &= \prod_{j=1}^p \exp \left(\frac{1}{2} t^T L_j L_j^T t \right) \\ &= \exp \left(\frac{1}{2} \sum_{j=1}^p t^T L_j L_j^T t \right) \\ &= \exp \left(\frac{1}{2} t^T L L^T t \right) \end{aligned}$$

Come back to the MGF of x :

$$E(\exp(t^T x)) = \exp \left(t^T \mu + \frac{1}{2} t^T L L^T t \right)$$

Therefore, $x \sim N(\mu, L L^T)$.

E

We have that x has a multivariate normal distribution: $x \sim N(\mu, \Sigma)$. The covariance matrix Σ is symmetric positive definite and has a Cholesky decomposition:

$$\Sigma = LL^T$$

where L is a lower triangular matrix with positive diagonal entries and therefore invertible. Let

$$z = L^{-1}(x - \mu)$$

Consider the MGF of z :

$$\begin{aligned} E[\exp(t^T z)] &= E[\exp(t^T L^{-1}(x - \mu))] \\ &= E[\exp(t^T L^{-1}x) \cdot \exp(-t^T L^{-1}\mu)] \\ &= \text{MGF}_x(t^T L^{-1}) \cdot \exp(-t^T L^{-1}\mu) \\ &= \exp(t^T L^{-1}\mu + t^T L^{-1}\Sigma L^{-T}t/2) \cdot \exp(-t^T L^{-1}\mu) \\ &= \exp(t^T L^{-1}\Sigma L^{-T}t/2) \\ &= \exp(t^T L^{-1}(LL^T)L^{-T}t/2) \\ &= \exp(t^T t/2) \end{aligned}$$

We conclude that z has standard multivariate normal distribution and that x can be written as an affine transformation of standard normal distribution.

F

Let z be standard multivariate Normal:

$$p_Z(z) \propto \exp\left(-\frac{z^T z}{2}\right)$$

By the previous result, we have that $x = Lz + \mu$ has multivariate Normal distribution. Since L is full rank, it is invertible, let $z = f(x) = L^{-1}(x - \mu)$

The pdf of x is:

$$\begin{aligned} p_X(x) &= p_Z(f(x))|J_f(x)| \\ &\propto \exp\left(-\frac{(x - \mu)^T L^{-T} L^{-1}(x - \mu)}{2}\right) |L^{-1}| \\ &\propto \exp(-Q(x - \mu)/2) \end{aligned}$$

G

By the previous results, x_1 and x_2 are affine transformation of independent standard Normal distribution. Let $z \sim N(0, I)$

$$\begin{aligned}x_1 &= L_1 z + \mu_1 \\x_2 &= L_2 z + \mu_2\end{aligned}$$

We have:

$$\begin{aligned}y &= Ax_1 + Bx_2 = AL_1 z + A\mu_1 + BL_2 z + B\mu_2 \\&= (AL_1 + BL_2)z + A\mu_1 + B\mu_2\end{aligned}$$

We see that y is an affine transformation of independent standard Normal variables and therefore is multivariate Normal with mean $A\mu_1 + B\mu_2$ and variance

$$\begin{aligned}(AL_1 + BL_2)(AL_1 + BL_2)^T &= AL_1 L_1^T A^T + AL_1 L_2^T B^T + BL_2 L_1^T A^T + BL_2 L_2^T B^T \\&= A\Sigma_1 A^T + AL_1 L_2^T B^T + BL_2 L_1^T A^T + B\Sigma_2 B^T\end{aligned}$$

3 Conditionals and marginals

A

Decompose the covariance matrix Σ and partition L into L_1 and L_2 where L_1 has k elements and corresponds to x_1 .

$$\begin{aligned}\Sigma &= LL^T \\&= \begin{pmatrix} L_1 \\ L_2 \end{pmatrix} \begin{pmatrix} L_1^T & L_2^T \end{pmatrix} \\&= \begin{pmatrix} L_1 L_1^T & L_1 L_2^T \\ L_2 L_1^T & L_2 L_2^T \end{pmatrix}\end{aligned}$$

We have that $\Sigma_{11} = L_1 L_1^T$. By the previous results, $x = Lz + \mu$ where z is a vector of independent standard Normal variables. Take the first k element, we have:

$$x_1 = L_1 z_1 + \mu_1$$

where z_1 is also a vector of independent standard Normal variables. Therefore, x_1 also has multivariate Normal distribution with mean μ_1 and variance $L_1 L_1^T = \Sigma_{11}$.

B

$$\begin{aligned} \begin{pmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{pmatrix}^{-1} &= \begin{pmatrix} (\Sigma_{11} - \Sigma_{12}\Sigma_{22}^{-1}\Sigma_{21})^{-1} & -\Sigma_{11}^{-1}\Sigma_{12}(\Sigma_{22} - \Sigma_{21}\Sigma_{11}^{-1}\Sigma_{12})^{-1} \\ -\Sigma_{22}^{-1}\Sigma_{21}(\Sigma_{11} - \Sigma_{12}\Sigma_{22}^{-1}\Sigma_{21})^{-1} & (\Sigma_{22} - \Sigma_{21}\Sigma_{11}^{-1}\Sigma_{12})^{-1} \end{pmatrix} \\ &= \begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{12}^T & \Omega_{22} \end{pmatrix} \end{aligned}$$

C

$$\begin{aligned} \log p(x_1|x_2) &= \log p(x_1, x_2) - \log(x_2) \\ &= \text{const} - \frac{(x - \mu)^T \Sigma^{-1} (x - \mu)}{2} \\ &= \text{const} - \frac{1}{2} \left\{ \begin{pmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{pmatrix}^T \begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{12}^T & \Omega_{22} \end{pmatrix} \begin{pmatrix} x_1 - \mu_1 \\ x_2 - \mu_2 \end{pmatrix} \right\} \\ &= \text{const} - \frac{1}{2} \{ (x_1 - \mu_1)^T \Omega_{11} (x_1 - \mu_1) + (x_2 - \mu_2)^T \Omega_{12}^T (x_1 - \mu_1) \\ &\quad + (x_1 - \mu_1)^T \Omega_{12} (x_2 - \mu_2) + (x_2 - \mu_2)^T \Omega_{22}^T (x_2 - \mu_2) \} \\ &= \text{const} - \frac{1}{2} \{ (x_1 - \mu_1)^T \Omega_{11} (x_1 - \mu_1) + 2(x_1 - \mu_1)^T \Omega_{12} (x_2 - \mu_2) \} \\ &= \text{const} - \frac{1}{2} \{ x_1^T \Omega_{11} x_1 - x_1^T \Omega_{11} \mu_1 - \mu_1^T \Omega_{11} x_1 + 2x_1^T \Omega_{12} x_2 - 2x_1^T \Omega_{12} \mu_2 \} \\ &= \text{const} - \frac{1}{2} \{ x_1^T (\Omega_{11} x_1 - \Omega_{11} \mu_1 - \Omega_{11}^T \mu_1 + 2\Omega_{12} x_2 - 2\Omega_{12} \mu_2) \} \end{aligned}$$