Chapter 7

stevenjin8

October 4, 2020

1 Proofs

Equation 7.54

One of the results that I did not find trivial was equation 7.54. Perhaps it was proven somewhere in Chapter 4. I prove the in this subsection. As a reminder, the equation in question is

$$p(\mathbf{y}|\mathbf{X}, \mathbf{w}, \sigma^2) \propto \exp(-\frac{1}{2\sigma^2}\|\mathbf{y} - \bar{y}\mathbf{1}_N - \mathbf{X}\mathbf{w}\|_2^2).$$

As the author says, we must "integrate [μ] out":

$$p(\mathbf{y}|\mathbf{X}, \mathbf{w}, \sigma^2) = \int p(\mathbf{y}, \mu|\mathbf{X}, \mathbf{w}, \sigma^2) d\mu.$$

Since μ is independent and $p(\mu)$ is constant for all $\mu \in \mathbb{R}$,

$$\begin{aligned} p(\mathbf{y}|\mathbf{X}, \mathbf{w}, \sigma^2) &\propto \int p(\mathbf{y}|\mathbf{X}, \mathbf{w}, \mu, \sigma^2) d\mu \\ &\propto \int \exp\left(\frac{(\mathbf{y} - \mu\mathbf{1}_N - \mathbf{X}\mathbf{w})^2}{-2\sigma^2}\right) d\mu. \end{aligned}$$

In this section, $\mathbf{v}^2 = \mathbf{v}.\mathbf{v}$ for any vector $\mathbf{v}$.

Next, we expand and take all terms that are independent of μ out of the integral:

$$\begin{aligned} &p(\mathbf{y}|\mathbf{X}, \mathbf{w}, \sigma^2) \propto \\ &\int \exp\left(\frac{\mathbf{y}^2 - 2\mathbf{y}.(\mu\mathbf{1}) + (\mu\mathbf{1})^2 + 2(\mu\mathbf{1}).(\mathbf{X}\mathbf{w}) + (\mathbf{X}\mathbf{w})^2 + 2(\mathbf{X}\mathbf{w}).\mathbf{y}}{-2\sigma^2}\right) d\mu \\ &\propto \exp\left(\frac{\mathbf{y}^2 + 2(\mathbf{X}\mathbf{w}).\mathbf{y} + (\mathbf{X}\mathbf{w})^2}{-2\sigma^2}\right) \\ &\qquad \int \exp\left(\frac{-2\mathbf{y}.(\mu\mathbf{1}) + (\mu\mathbf{1})^2 + 2(\mu\mathbf{1}).(\mathbf{X}\mathbf{w})}{-2\sigma^2}\right) d\mu. \end{aligned}$$

Since $\sum_i x_{ij} = 0$, we can ignore $\mu\mathbf{1}.\mathbf{X}\mathbf{w}$, and complete the square:

$$\begin{aligned}
&\int \exp\left(\frac{-2\mathbf{y}.(\mu\mathbf{1}) + (\mu\mathbf{1})^2 + (\mu\mathbf{1}).(\mathbf{X}\mathbf{w})}{-2\sigma^2}\right) d\mu \\
&= \int \exp\left(\frac{N(-2\mu\bar{y} + \mu^2)}{-2\sigma^2}\right) d\mu \\
&= \exp\left(\frac{-N\bar{y}^2}{-2\sigma^2}\right) \int \exp\left(\frac{N(\mu - \bar{y})^2}{-2\sigma^2}\right) d\mu \\
&\propto \exp\left(\frac{-N\bar{y}^2}{-2\sigma^2}\right) \\
&= \exp\left(\frac{-(\bar{y}\mathbf{1})^2}{-2\sigma^2}\right)
\end{aligned} \tag{1}$$

Plugging this result back into equation (1) yields

$$\begin{aligned}
p(\mathbf{y}|\mathbf{X}, \mathbf{w}, \sigma^2) &\propto \exp\left(\frac{\mathbf{y}^2 - (\bar{y}\mathbf{1})^2 - 2(\mathbf{X}\mathbf{w}).\mathbf{y} + (\mathbf{X}\mathbf{w})^2}{-2\sigma^2}\right) \\
&= \exp\left(\frac{(\mathbf{y} - \bar{y}\mathbf{1})^2 - 2(\mathbf{X}\mathbf{w}).\mathbf{y} + (\mathbf{X}\mathbf{w})^2}{-2\sigma^2}\right) \\
&= \exp\left(\frac{(\mathbf{y} - \bar{y}\mathbf{1})^2 - 2(\mathbf{X}\mathbf{w}).(\mathbf{y} - \bar{y}\mathbf{1}) + (\mathbf{X}\mathbf{w})^2}{-2\sigma^2}\right) \\
&= \exp(-\frac{1}{2\sigma^2}\|\mathbf{y} - \bar{y}\mathbf{1}_N - \mathbf{X}\mathbf{w}\|_2^2).
\end{aligned} \tag{2}$$

Exercises

Exercise 9

In this exercise we use the results of section 4.3.1 to arrive at the same formula as that of exercise 7.5:

$$\mathbb{E}[y|\mathbf{x}] = \bar{y} - \mathbf{w}^T\bar{\mathbf{x}} + \mathbf{w}^T\mathbf{x}$$

(this formula is not the exact one given in the question but they are equivalent). First, we find the covariance matrices $\mathbf{\Sigma}_{XX}$ and $\mathbf{\Sigma}_{XY}$ of the joint distribution:

$$\begin{aligned}
\mathbf{\Sigma} &= \begin{pmatrix} \mathbf{\Sigma}_{YY} & \mathbf{\Sigma}_{YX} \\ \mathbf{\Sigma}_{XY} & \mathbf{\Sigma}_{XX} \end{pmatrix} \\
&= \begin{pmatrix} \mathbf{y} & \mathbf{X} \end{pmatrix}^T \begin{pmatrix} \mathbf{y} & \mathbf{X} \end{pmatrix} \\
&= \begin{pmatrix} \mathbf{y}^T\mathbf{y} & \mathbf{y}^T\mathbf{X} \\ \mathbf{X}^T\mathbf{y} & \mathbf{X}^T\mathbf{X} \end{pmatrix}.
\end{aligned}$$

Thus,

$$\begin{aligned} \mathbf{\Sigma}_{XX} &= \mathbf{X}^T\mathbf{X} \\ \mathbf{\Sigma}_{YX} &= \mathbf{y}^T\mathbf{X}. \end{aligned} \tag{3}$$

I know the question said to find $\mathbf{\Sigma}_{XY}$, but I think we are supposed to find $\mathbf{\Sigma}_{YX}$. Finding the means $\boldsymbol{\mu}_x$ and $\boldsymbol{\mu}_y$ is a lot easier:

$$\begin{aligned} \boldsymbol{\mu}_x &= \bar{\mathbf{x}} = \frac{1}{N}\sum \mathbf{x}_i \\ \mu_y &= \bar{y} = \frac{1}{N}\sum y_i. \end{aligned} \tag{4}$$

Now, we plug (3) and (4) into equation 4.69 and replace 1 with y and 2 with x. Given $\mathbf{x}$ our prediction for y is

$$\begin{aligned} \mu_{y|x} &= \mu_y + \mathbf{\Sigma}_{YX}\mathbf{\Sigma}_{XX}^{-1}(\mathbf{x} - \bar{\mathbf{x}}) \\ &= \bar{y} + \mathbf{y}\mathbf{X}^T(\mathbf{X}^T\mathbf{X})^{-1}(\mathbf{x} - \bar{\mathbf{x}}) \\ &= \bar{y} + ((\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{y})^T(\mathbf{x} - \bar{\mathbf{x}}) \\ &= \bar{y} + -\mathbf{w}^T\bar{\mathbf{x}} + \mathbf{w}^T\mathbf{x} \\ &= \mathbb{E}[y|\mathbf{x}]. \end{aligned}$$

Recall that $\mathbf{X}^T\mathbf{X}$ is symmetric so $(\mathbf{X}^T\mathbf{X})^{-T} = (\mathbf{X}^T\mathbf{X})^{-1}$. I find it reassuring that the discriminative and generative approach converge to the same solution. That being said, I am not sure what the author is looking for in part b) as in both approaches, one ends up doing the same calculations.