

# Solutions Manual to Pattern Recognition and Machine Learning

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# 1 Introduction

## 1.1

To minimise

$$E(\mathbf{w}) = \frac{1}{2} \sum_{n=1}^N (y(x_n, \mathbf{w}) - t_n)^2, \quad (1.1)$$

setting its derivative to zero gives

$$\mathbf{0} = \sum_{n=1}^N \frac{\partial y(x_n, \mathbf{w})}{\partial \mathbf{w}} (y(x_n, \mathbf{w}) - t_n). \quad (1.2)$$

Substituting

$$y(x_n, \mathbf{w}) = \sum_{j=0}^M w_j x_n^j \quad (1.3)$$

gives

$$0 = \sum_{n=1}^N x_n^i \left( \sum_{j=0}^M w_j x_n^j - t_n \right). \quad (1.4)$$

Therefore,

$$\sum_{j=0}^M A_{ij} w_j = T_i \quad (1.5)$$

where

$$\begin{aligned} A_{ij} &= \sum_{n=1}^N x_n^{i+j}, \\ T_i &= \sum_{n=1}^N x_n^i t_n. \end{aligned} \quad (1.6)$$

## 1.2

To minimise

$$\tilde{E}(\mathbf{w}) = \frac{1}{2} \sum_{n=1}^N (y(x_n, \mathbf{w}) - t_n)^2 + \frac{\lambda}{2} \|\mathbf{w}\|^2, \quad (1.7)$$

setting its derivative to zero gives

$$\mathbf{0} = \sum_{n=1}^N \frac{\partial y(x_n, \mathbf{w})}{\partial \mathbf{w}} (y(x_n, \mathbf{w}) - t_n) + \lambda \mathbf{w}. \quad (1.8)$$

Substituting

$$y(x_n, \mathbf{w}) = \sum_{j=0}^M w_j x_n^j \quad (1.9)$$

gives

$$0 = \sum_{n=1}^N x_n^i \left( \sum_{j=0}^M w_j x_n^j - t_n \right) + \lambda w_i. \quad (1.10)$$

Therefore,

$$\sum_{j=0}^M \tilde{A}_{ij} w_j = T_i \quad (1.11)$$

where

$$\begin{aligned} \tilde{A}_{ij} &= \sum_{n=1}^N x_n^{i+j} + \lambda \delta_{ij}, \\ T_i &= \sum_{n=1}^N x_n^i t_n. \end{aligned} \quad (1.12)$$

### 1.3

Let  $a$ ,  $o$  and  $l$  be the events where an apple, orange and lime are selected respectively. The probability that an apple is selected is given by

$$p(a) = p(a|r)p(r) + p(a|b)p(b) + p(a|g)p(g). \quad (1.13)$$

Substituting  $p(a|r) = \frac{3}{10}$ ,  $p(r) = \frac{1}{5}$ ,  $p(a|g) = \frac{1}{2}$ ,  $p(r) = \frac{1}{5}$ ,  $p(a|g) = \frac{3}{10}$  and  $p(g) = \frac{3}{5}$  gives

$$p(a) = \frac{17}{50}. \quad (1.14)$$

If an orange is selected, the probability that it came from the green box is given by

$$p(g|o) = \frac{p(g, o)}{p(o)}. \quad (1.15)$$

Here,

$$\begin{aligned} p(g, o) &= p(o|g)p(g), \\ p(o) &= p(o|r)p(r) + p(o|b)p(b) + p(o|g)p(g). \end{aligned} \quad (1.16)$$

Substituting  $p(o|r) = \frac{2}{5}$ ,  $p(r) = \frac{1}{5}$ ,  $p(o|b) = \frac{1}{2}$ ,  $p(b) = \frac{1}{5}$ ,  $p(o|g) = \frac{3}{10}$  and  $p(g) = \frac{3}{5}$  gives  $p(g, o) = \frac{9}{50}$  and  $p(o) = \frac{9}{25}$ . Therefore,

$$p(g|o) = \frac{1}{2}. \quad (1.17)$$

## 1.5

By the definition,

$$\text{var } f(x) = E(f(x) - Ef(x))^2. \quad (1.18)$$

The right hand side can be written as

$$E((f(x))^2 - 2f(x)Ef(x) + (Ef(x))^2) = E(f(x))^2 - (Ef(x))^2. \quad (1.19)$$

Therefore,

$$\text{var } f(x) = E(f(x))^2 - (Ef(x))^2. \quad (1.20)$$

## 1.6

By the definition,

$$\text{cov}(x, y) = E((x - Ex)(y - Ey)). \quad (1.21)$$

The right hand side can be written as

$$Exy - E(xEy) - E(yEx) + E(ExEy) = Exy - ExEy. \quad (1.22)$$

The right hand side can be written as

$$\int xyp(x, y)dxdy - \int xp(x)dx \int yp(y)dy. \quad (1.23)$$

If  $x$  and  $y$  are independent, by the definition,

$$f(x, y) = f(x)f(y). \quad (1.24)$$

Then,

$$\int xyp(x, y)dxdy = \int p(x)dx \int p(y)dy. \quad (1.25)$$

Therefore,

$$\text{cov}(x, y) = 0. \quad (1.26)$$

## 1.7

Let

$$I = \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2\sigma^2}x^2\right) dx. \quad (1.27)$$

Then

$$I^2 = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2\sigma^2}(x^2 + y^2)\right) dx dy. \quad (1.28)$$

By the transformation from Cartesian coordinates  $(x, y)$  to polar coordinates  $(r, \theta)$ , the right hand side can be written as

$$\int_0^{\infty} \int_0^{2\pi} \exp\left(-\frac{1}{2\sigma^2}r^2\right) \begin{vmatrix} \cos \theta & -r \sin \theta \\ \sin \theta & r \cos \theta \end{vmatrix} dr d\theta = 2\pi \int_0^{\infty} \exp\left(-\frac{1}{2\sigma^2}r^2\right) r dr. \quad (1.29)$$

By the transformation  $s = \frac{r}{\sigma}$ , the right hand side can be written as

$$2\pi\sigma^2 \int_0^{\infty} \exp\left(-\frac{1}{2}s^2\right) s ds = 2\pi\sigma^2 \left[-\exp\left(-\frac{1}{2}s^2\right)\right]_0^{\infty}. \quad (1.30)$$

Therefore,

$$I = (2\pi\sigma^2)^{\frac{1}{2}}. \quad (1.31)$$

By the definition,

$$\mathcal{N}(x|\mu, \sigma^2) = (2\pi\sigma^2)^{-\frac{1}{2}} \exp\left(-\frac{1}{2\sigma^2}(x - \mu)^2\right). \quad (1.32)$$

Then

$$\int_{-\infty}^{\infty} \mathcal{N}(x|\mu, \sigma^2) dx = (2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2\sigma^2}(x - \mu)^2\right) dx. \quad (1.33)$$

By the transformation  $t = x - \mu$ , the right hand side can be written as

$$(2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2\sigma^2}t^2\right) dt = (2\pi\sigma^2)^{-\frac{1}{2}} I. \quad (1.34)$$

Therefore,

$$\int_{-\infty}^{\infty} \mathcal{N}(x|\mu, \sigma^2) dx = 1. \quad (1.35)$$

## 1.8

If  $x$  is under the Gaussian distribution with mean  $\mu$  and variance  $\sigma^2$ , then

$$\mathbb{E}x = \int_{-\infty}^{\infty} x \mathcal{N}(x|\mu, \sigma^2) dx. \quad (1.36)$$

By the definition, the right hand side can be written as

$$(2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} x \exp\left(-\frac{1}{2\sigma^2}(x-\mu)^2\right) dx. \quad (1.37)$$

By the transformation  $y = x - \mu$ , it can be written as

$$(2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} (y + \mu) \exp\left(-\frac{1}{2\sigma^2}y^2\right) dy. \quad (1.38)$$

Since

$$(2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} y \exp\left(-\frac{1}{2\sigma^2}y^2\right) dy = 0, \quad (1.39)$$

and

$$(2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} \mu \exp\left(-\frac{1}{2\sigma^2}y^2\right) dy = \mu \int_{-\infty}^{\infty} \mathcal{N}(y|\mu, \sigma^2) dy, \quad (1.40)$$

we have

$$\mathbb{E}x = \mu. \quad (1.41)$$

By the definition,

$$\int_{-\infty}^{\infty} \mathcal{N}(x|\mu, \sigma^2) dx = 1 \quad (1.42)$$

can be written as

$$(2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2\sigma^2}(x-\mu)^2\right) dx = 1. \quad (1.43)$$

Differentiating both sides with respect to  $\sigma^2$  gives

$$\begin{aligned} & (2\pi)^{-\frac{1}{2}} \left(-\frac{1}{2}\right) (\sigma^2)^{-\frac{3}{2}} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2\sigma^2}(x-\mu)^2\right) dx \\ & + (2\pi\sigma^2)^{-\frac{1}{2}} \int_{-\infty}^{\infty} \frac{1}{2} (\sigma^2)^{-2} (x-\mu)^2 \exp\left(-\frac{1}{2\sigma^2}(x-\mu)^2\right) dx = 0. \end{aligned} \quad (1.44)$$

The left hand side can be written as

$$\begin{aligned} -\frac{1}{2} (\sigma^2)^{-1} \int_{-\infty}^{\infty} \mathcal{N}(x|\mu, \sigma^2) dx + \frac{1}{2} (\sigma^2)^{-2} \int_{-\infty}^{\infty} (x - \mu)^2 \mathcal{N}(x|\mu, \sigma^2) dx \\ = -\frac{1}{2} (\sigma^2)^{-1} + \frac{1}{2} (\sigma^2)^{-2} \text{var} x. \end{aligned} \quad (1.45)$$

Therefore,

$$\text{var} x = \sigma^2. \quad (1.46)$$

## 1.9

By the definition,

$$\mathcal{N}(x|\mu, \sigma^2) = (2\pi\sigma^2)^{-\frac{1}{2}} \exp\left(-\frac{1}{2\sigma^2}(x - \mu)^2\right). \quad (1.47)$$

Setting its derivative to zero gives

$$0 = (2\pi\sigma^2)^{-\frac{1}{2}} \left(-\frac{1}{\sigma^2}(x - \mu)\right) \exp\left(-\frac{1}{2\sigma^2}(x - \mu)^2\right). \quad (1.48)$$

Therefore, the mode is given by  $\mu$ .

Similarly, by the definition,

$$\mathcal{N}(\mathbf{x}|\boldsymbol{\mu}, \boldsymbol{\Sigma}) = (2\pi)^{-\frac{D}{2}} |\boldsymbol{\Sigma}|^{-\frac{1}{2}} \exp\left(-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^\top \boldsymbol{\Sigma}^{-1}(\mathbf{x} - \boldsymbol{\mu})\right). \quad (1.49)$$

Setting its derivative to zero gives

$$\mathbf{0} = -(2\pi)^{-\frac{D}{2}} |\boldsymbol{\Sigma}|^{-\frac{1}{2}} (\boldsymbol{\Sigma}^{-1} + (\boldsymbol{\Sigma}^{-1})^\top) (\mathbf{x} - \boldsymbol{\mu}) \exp\left(-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^\top \boldsymbol{\Sigma}^{-1}(\mathbf{x} - \boldsymbol{\mu})\right). \quad (1.50)$$

Therefore, the mode is given by  $\boldsymbol{\mu}$ .

## 1.10

By the definition,

$$\mathbb{E}(x + y) = \int \int (x + y) p(x, y) dx dy. \quad (1.51)$$

The right hand side can be written as

$$\int x \left( \int p(x, y) dy \right) dx + \int y \left( \int p(x, y) dx \right) dy = \int xp(x) dx + \int yp(y) dy. \quad (1.52)$$

By the definition, the right hand side can be written as

$$Ex + Ey. \quad (1.53)$$

Therefore,

$$E(x + y) = Ex + Ey. \quad (1.54)$$

Similarly, by the definition,

$$\text{var}(x + y) = E(x + y - E(x + y))^2 \quad (1.55)$$

By the result above and the definition, the right hand side can be written as

$$\begin{aligned} E(x - Ex)^2 + 2E((x - Ex)(y - Ey)) + E(y - Ey)^2 \\ = \text{var}x + 2\text{cov}(x, y) + \text{var}y. \end{aligned} \quad (1.56)$$

If  $x$  and  $y$  are independent, then

$$\text{cov}(x, y) = 0, \quad (1.57)$$

by 1.6. Therefore,

$$\text{var}(x + y) = \text{var}x + \text{var}y. \quad (1.58)$$

## 1.11

To maximise

$$\ln p(\mathbf{x}|\mu, \sigma^2) = -\frac{N}{2} \ln(2\pi\sigma^2) - \frac{1}{2\sigma^2} \sum_{n=1}^N (x_n - \mu)^2, \quad (1.59)$$

setting the partial derivatives with respect to  $\mu$  and  $\sigma^2$  to zero gives

$$\begin{aligned} 0 &= \frac{1}{\sigma^2} \sum_{n=1}^N (x_n - \mu), \\ 0 &= -\frac{N}{2\sigma^2} + \frac{1}{2(\sigma^2)^2} \sum_{n=1}^N (x_n - \mu)^2. \end{aligned} \quad (1.60)$$



Therefore,

$$\begin{aligned}\mu_{\text{ML}} &= \frac{1}{N} \sum_{n=1}^N x_n, \\ \sigma_{\text{ML}}^2 &= \frac{1}{N} \sum_{n=1}^N (x_n - \mu_{\text{ML}})^2.\end{aligned}\tag{1.61}$$

### 1.12

If  $x_m$  and  $x_n$  are independent, then

$$\mathbb{E}x_mx_n = \mathbb{E}x_m\mathbb{E}x_n.\tag{1.62}$$

If they are samples from the Gaussian distribution with mean  $\mu$  and variance  $\sigma^2$ , the right hand side is given by  $\mu^2$ . On the other hand, by the definition,

$$\mathbb{E}x_n^2 = \text{var}x_n + (\mathbb{E}x_n)^2.\tag{1.63}$$

If  $x_n$  is a sample from the Gaussian distribution with mean  $\mu$  and variance  $\sigma^2$ , the right hand side is given by  $\sigma^2 + \mu^2$ . Therefore,

$$\mathbb{E}x_mx_n = \mu^2 + \delta_{mn}\sigma^2.\tag{1.64}$$

Here, since

$$\mu_{\text{ML}} = \frac{1}{N} \sum_{n=1}^N x_n,\tag{1.65}$$

we have

$$\mathbb{E}\mu_{\text{ML}} = \frac{1}{N} \sum_{n=1}^N \mathbb{E}x_n.\tag{1.66}$$

Therefore,

$$\mathbb{E}\mu_{\text{ML}} = \mu.\tag{1.67}$$

Similarly, since

$$\sigma_{\text{ML}}^2 = \frac{1}{N} \sum_{n=1}^N (x_n - \mu_{\text{ML}})^2,\tag{1.68}$$

we have

$$\mathbb{E}\sigma_{\text{ML}}^2 = \frac{1}{N} \sum_{n=1}^N \mathbb{E}(x_n - \mu_{\text{ML}})^2.\tag{1.69}$$

The right hand side can be written as

$$\frac{1}{N} \sum_{n=1}^N \mathbb{E} (x_n^2 - 2\mu_{\text{ML}}x_n + \mu_{\text{ML}}^2) = \frac{1}{N} \sum_{n=1}^N \mathbb{E} x_n^2 - \frac{2}{N} \mathbb{E} \left( \mu_{\text{ML}} \left( \sum_{n=1}^N x_n \right) \right) + \mathbb{E} \mu_{\text{ML}}^2. \quad (1.70)$$

The first term of the right hand side can be written as

$$\frac{1}{N} \sum_{n=1}^N (\mu^2 + \sigma^2) = \mu^2 + \sigma^2, \quad (1.71)$$

while the second and third terms can be written as

$$-2\mathbb{E} \mu_{\text{ML}}^2 + \mathbb{E} \mu_{\text{ML}}^2 = -\mathbb{E} \mu_{\text{ML}}^2. \quad (1.72)$$

Here,

$$\mathbb{E} \mu_{\text{ML}}^2 = \mathbb{E} \left( \frac{1}{N} \sum_{n=1}^N x_n \right)^2. \quad (1.73)$$

The right hand side can be written as

$$\frac{1}{N^2} \sum_{n=1}^N \mathbb{E} x_n^2 + \frac{2}{N^2} \sum_{1 \leq m < n \leq N} \mathbb{E} x_m x_n = \frac{1}{N} (\mu^2 + \sigma^2) + \frac{N-1}{N} \mu^2. \quad (1.74)$$

Therefore,

$$\mathbb{E} \mu_{\text{ML}}^2 = \mu^2 + \frac{1}{N} \sigma^2. \quad (1.75)$$

Thus,

$$\mathbb{E} \sigma_{\text{ML}}^2 = \frac{N-1}{N} \sigma^2. \quad (1.76)$$

### 1.13

It is clear that

$$\mathbb{E} \left( \frac{1}{N} \sum_{n=1}^N (x_n - \mu)^2 \right) = \frac{1}{N} \sum_{n=1}^N \mathbb{E} (x_n - \mu)^2. \quad (1.77)$$

The right hand side can be written as

$$\frac{1}{N} \sum_{n=1}^N \mathbb{E} (x_n^2 - 2\mu x_n + \mu^2) = \frac{1}{N} \sum_{n=1}^N \mathbb{E} x_n^2 - \frac{2\mu}{N} \sum_{n=1}^N \mathbb{E} x_n + \mu^2. \quad (1.78)$$

The first term of the right hand side can be written as

$$\frac{1}{N} \sum_{n=1}^N (\mu^2 + \sigma^2) = \mu^2 + \sigma^2, \quad (1.79)$$

while the second term can be written as

$$-\frac{2\mu}{N} \sum_{n=1}^N \mu = -2\mu^2. \quad (1.80)$$

Therefore,

$$\mathbb{E} \left( \frac{1}{N} \sum_{n=1}^N (x_n - \mu)^2 \right) = \sigma^2. \quad (1.81)$$

## 1.14

Let

$$\begin{aligned} w_{ij}^S &= \frac{1}{2}(w_{ij} + w_{ji}), \\ w_{ij}^A &= \frac{1}{2}(w_{ij} - w_{ji}). \end{aligned} \quad (1.82)$$

Then

$$\begin{aligned} w_{ij} &= w_{ij}^S + w_{ij}^A, \\ w_{ij}^S &= w_{ji}^S, \\ w_{ij}^A &= -w_{ji}^A. \end{aligned} \quad (1.83)$$

Here,

$$\sum_{i=1}^D \sum_{j=1}^D w_{ij}^A x_i x_j = \frac{1}{2} \sum_{i=1}^D \sum_{j=1}^D (w_{ij} - w_{ji}) x_i x_j. \quad (1.84)$$

The right hand side can be written as

$$\frac{1}{2} \left( \sum_{i=1}^D \sum_{j=1}^D w_{ij} x_i x_j - \sum_{i=1}^D \sum_{j=1}^D w_{ji} x_i x_j \right) = 0. \quad (1.85)$$

Therefore,

$$\sum_{i=1}^D \sum_{j=1}^D w_{ij}^A x_i x_j = 0. \quad (1.86)$$

Additionally,

$$\sum_{i=1}^D \sum_{j=1}^D w_{ij} x_i x_j = \sum_{i=1}^D \sum_{j=1}^D (w_{ij}^S + w_{ij}^A) x_i x_j. \quad (1.87)$$

The right hand side can be written as

$$\sum_{i=1}^D \sum_{j=1}^D w_{ij}^S x_i x_j + \sum_{i=1}^D \sum_{j=1}^D w_{ij}^A x_i x_j = \sum_{i=1}^D \sum_{j=1}^D w_{ij}^S x_i x_j, \quad (1.88)$$

where the result above is used. Therefore,

$$\sum_{i=1}^D \sum_{j=1}^D w_{ij} x_i x_j = \sum_{i=1}^D \sum_{j=1}^D w_{ij}^S x_i x_j. \quad (1.89)$$

Finally, since the matrix  $w_{ij}^S$  is  $D \times D$  symmetric matrix, its number of independent parameters is  $\frac{D(D+1)}{2}$ .

## 1.17

By the definition,

$$\Gamma(x) = \int_0^\infty u^{x-1} \exp(-u) du. \quad (1.90)$$

Then

$$\Gamma(x+1) = \int_0^\infty u^x \exp(-u) du. \quad (1.91)$$

The right hand side can be written as

$$[-u^x \exp(-u)]_{u=0}^{u=\infty} + \int_0^\infty x u^{x-1} \exp(-u) du = x \Gamma(x). \quad (1.92)$$

Therefore,

$$\Gamma(x+1) = x \Gamma(x). \quad (1.93)$$

By the definition,

$$\Gamma(1) = \int_0^1 \exp(-u) du. \quad (1.94)$$

The right hand side can be written as

$$[-\exp(-u)]_0^\infty = 1. \quad (1.95)$$

Therefore,

$$\Gamma(1) = 0!. \quad (1.96)$$

For a positive integer  $x$ , let us assume that

$$\Gamma(x) = (x-1)!. \quad (1.97)$$

Then,

$$\Gamma(x+1) = x\Gamma(x), \quad (1.98)$$

where the right hand side can be written as

$$x(x-1)! = x!. \quad (1.99)$$

Therefore,

$$\Gamma(x+1) = x!. \quad (1.100)$$

Thus, the assumption is proved by induction on  $x$ .

## 1.18

Let us consider the transformation from Cartesian to polar coordinates

$$\prod_{i=1}^D \int_{-\infty}^{\infty} \exp(-x_i^2) dx_i = S_D \int_0^{\infty} \exp(-r^2) r^{D-1} dr, \quad (1.101)$$

where  $S_D$  is the surface area of a sphere of unit radius in  $D$  dimensions. By 1.7, the left hand side can be written as  $\pi^{\frac{D}{2}}$ . By the transformation  $s = r^2$ , the right hand side can be written as

$$\frac{S_D}{2} \int_0^{\infty} \exp(-s) s^{\frac{D-1}{2}} s^{-\frac{1}{2}} ds = \frac{S_D}{2} \Gamma\left(\frac{D}{2}\right). \quad (1.102)$$

Therefore,

$$S_D = \frac{2\pi^{\frac{D}{2}}}{\Gamma\left(\frac{D}{2}\right)}. \quad (1.103)$$

Additionally, the volume of the sphere can be written as

$$V_D = S_D \int_0^1 r^{D-1} dr. \quad (1.104)$$

The right hand side can be written as

$$S_D \left[ \frac{r^D}{D} \right]_{r=0}^{r=1} = \frac{S_D}{D}. \quad (1.105)$$

Therefore,

$$V_D = \frac{S_D}{D}. \quad (1.106)$$

Finally, the results above reduce to

$$\begin{aligned} S_2 &= \frac{2\pi}{\Gamma(1)}, \\ V_2 &= \frac{S_2}{2}. \end{aligned} \quad (1.107)$$

Therefore,

$$\begin{aligned} S_2 &= 2\pi, \\ V_2 &= \pi. \end{aligned} \quad (1.108)$$

Similarly,

$$\begin{aligned} S_3 &= \frac{2\pi^{\frac{3}{2}}}{\Gamma(\frac{3}{2})}, \\ V_3 &= \frac{S_3}{3}. \end{aligned} \quad (1.109)$$

Therefore,

$$\begin{aligned} S_3 &= 4\pi, \\ V_3 &= \frac{4}{3}\pi. \end{aligned} \quad (1.110)$$