

# Statistical Methods of Machine Learning

## Assignment 1

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February 20, 2014

### I.1.1.1

Given

$$a = \begin{pmatrix} 1 \\ 2 \\ 2 \end{pmatrix} \quad b = \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

Then  $a^T b = 1 * 3 + 2 * 2 + 2 * 1 = 3 + 4 + 2 = 9$

### I.1.1.2

The  $l_2$ -norm or *Euclidean norm*  $\|a\| = \sqrt{1^2 + 2^2 + 2^2} = 3$

### I.1.1.3

The outer product

$$ab^T = \begin{bmatrix} 1 * 3 & 1 * 2 & 1 * 1 \\ 2 * 3 & 2 * 2 & 2 * 1 \\ 2 * 3 & 2 * 2 & 2 * 1 \end{bmatrix} = \begin{bmatrix} 3 & 2 & 1 \\ 6 & 4 & 2 \\ 6 & 4 & 2 \end{bmatrix}$$

### I.1.1.4

As  $M$  is a diagonal matrix the inverse matrix of  $M$  is

$$M^{-1} = \begin{bmatrix} 1/1 & 0 & 0 \\ 0 & 1/4 & 0 \\ 0 & 0 & 1/2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}$$

### I.1.1.5

The matrix-vector product  $Ma = \begin{pmatrix} 1 * 1 + 0 * 2 + 0 * 2 \\ 0 * 1 + 4 * 2 + 0 * 2 \\ 0 * 1 + 0 * 2 + 2 * 2 \end{pmatrix} = \begin{pmatrix} 1 \\ 8 \\ 2 \end{pmatrix}$

### I.1.1.6

$$A^T = (ab^T)^T = \begin{bmatrix} 3 & 6 & 6 \\ 2 & 4 & 4 \\ 1 & 2 & 2 \end{bmatrix}$$

### I.1.1.7

The rank of  $A = 1$ , because the rows are linearly dependent. We can verify this by observing that the first row can produce the second and third rows with a multiple, e.g. the second row  $(6 \ 4 \ 2)$  is the same as the first row  $(3 \ 2 \ 1) \times 2$ .

### I.1.1.8

As  $A$  is not full rank, it is not invertible.

### I.1.2.1

The derivative of  $f(w) = (wx + b)^2$  with respect to  $w$  is

$$\begin{aligned} ((wx + b)^2)' &= (w^2x^2 + 2wxb + b^2)' \\ &= 2x^2w + 2xb \\ &= 2x(wx + b) \end{aligned}$$

### I.1.2.2

In general

$$\left(\frac{f}{g}\right)'(x) = \frac{f'(x) \cdot g(x) - f(x) \cdot g'(x)}{(g(x))^2}$$

Therefore, differentiating for w we get:

$$\begin{aligned}f(x) &= 1 \\f'(x) &= 0 \\g(x) &= (wx + b)^2 \\g'(x) &= 2x(wx + b) \\ \left(\frac{f}{g}\right)'(w) &= \frac{0 \cdot (wx + b)^2 - 1 \cdot 2x(wx + b)}{((wx + b)^2)^2} \\ &= \frac{-1 \cdot 2x(wx + b)}{(wx + b)^4} \\ &= \frac{-2x}{(wx + b)^3}\end{aligned}$$

### I.1.2.3

In general

$$(f \cdot g)'(x) = f'(x) \cdot g(x) + f(x) \cdot g'(x)$$

Therefore, differentiating for x we get:

$$\begin{aligned}f(x) &= x \\f'(x) &= 1 \\g(x) &= e^x \\g'(x) &= e^x \\(f \cdot g)'(x) &= 1e^x + xe^x\end{aligned}$$

## I.2.1

The plots with gaussian distributions for  $(\mu, \sigma)$  pairs  $(-1, 1)$ ,  $(0, 2)$  and  $(2, 3)$  can be seen in Figure 1. The code for generating the plots can be found in `I_2_1.m`, and the code for our gaussian distribution function can be found in `unigauss.m`.

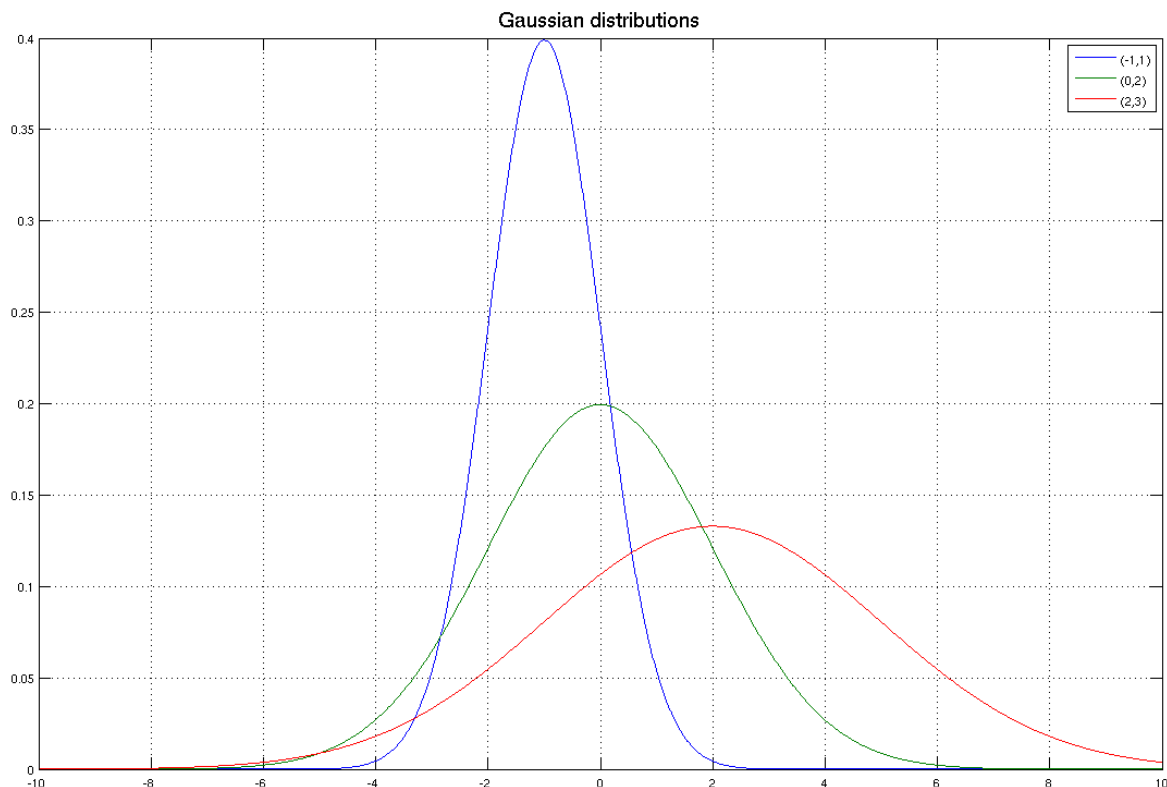


Figure 1: Gaussian distributions plotted with different values for  $(\mu, \sigma)$ .

## I.2.2

Source code is available in `multigauss.m` and `I_2_2.m`. Plot can be seen in Figure 2.

## I.2.3

The  $l_2$  norm of  $x$  is

$$\begin{aligned} \text{mean} &= \begin{pmatrix} 1 & 2 \end{pmatrix}^T \\ \mu &= \begin{pmatrix} 1.0006 & 1.9834 \end{pmatrix}^T \\ \|x\| &= l_2(\text{mean} - \mu) = 0.0366 \end{aligned}$$

where  $l_2()$  is a function that calculates the *Euclidean norm* or  $l_2$  norm of the vector  $\text{mean} - \mu$ .

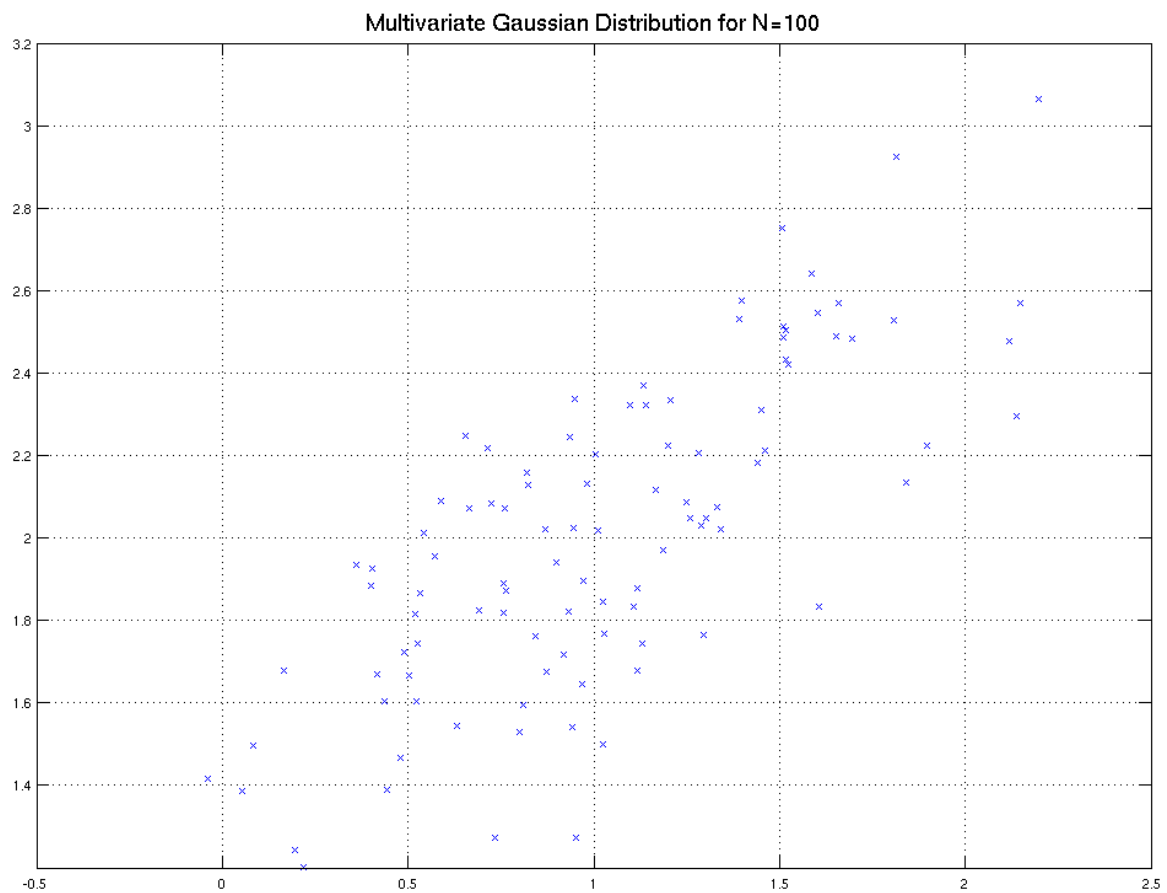


Figure 2: 100 points drawn from a 2-dimensional Multivariate gaussian distribution.

Figure 3 plots the points drawn along with a red circle for the calculated mean and a green circle for  $\mu$ . There is a difference between the two because the mean is calculated based on the generated data drawn from the multivariate gaussian distribution at random. If we had a number of points approaching infinite, the difference would approach 0. The source code for this exercise can be found in I\_2\_3.m.

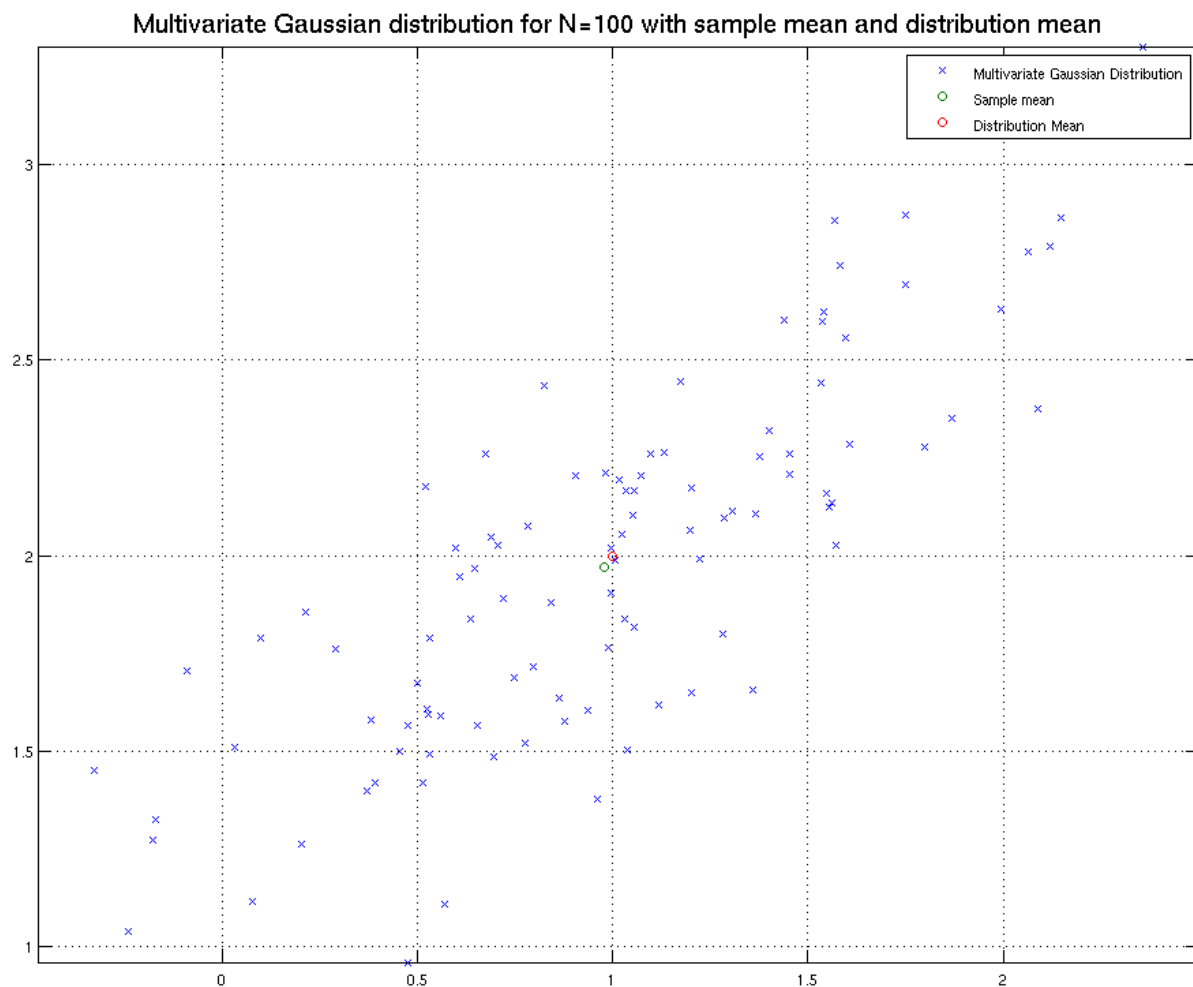


Figure 3: 100 points drawn from a 2-dimensional Multivariate gaussian distribution, plotted with the mean of the points and of  $\mu$ .

### I.2.4

The covariance matrix is full rank 2 and thus has two eigenvectors and eigenvalues. Each eigenvector represents a principal component (or linearly uncorrelated variable), and each eigenvalue a scalar representing the variance. Intuitively, the eigenvectors form a scaled and translated coordinate system centered at the mean of the multivariate Gaussian distribution ( $\mu$ ). If an eigenvalue is 0, the dimensionality is reduced by one. The larger of the two eigenvector/value pairs represents the direction where the ellipsis is widest. The other represents where the ellipsis is narrowest.

The covariance matrix we calculated can be found in Eq 1.

$$\begin{aligned}\Sigma_{ML} &= \frac{1}{N} \sum_{n=1}^N (x_n - \mu_{ML})(x_n - \mu_{ML})^T \\ &= \begin{pmatrix} 0.3239 & 0.2093 \\ 0.2093 & 0.2080 \end{pmatrix}\end{aligned}\tag{1}$$

Figure 4 shows a plot of the Multivariate gaussian distribution, plotted with the mean,  $\mu$  and the two eigenvectors centered in the distribution  $\mu$ . Figure 5 shows a plot of the 3 rotated distributions along with the distribution rotated to match the largest eigenvector along the x-axis. The angle needed for this was  $-37.2564^\circ$  in our case. Source code is available in `multigauss.m` and `I_2_4.m`. The angle is calculated by the formula

$$-\arctan(\text{eig}(\Sigma_{ML}))$$

which return the angle needed for rotating the distribution so its eigen vector is parallel to the x-axis.

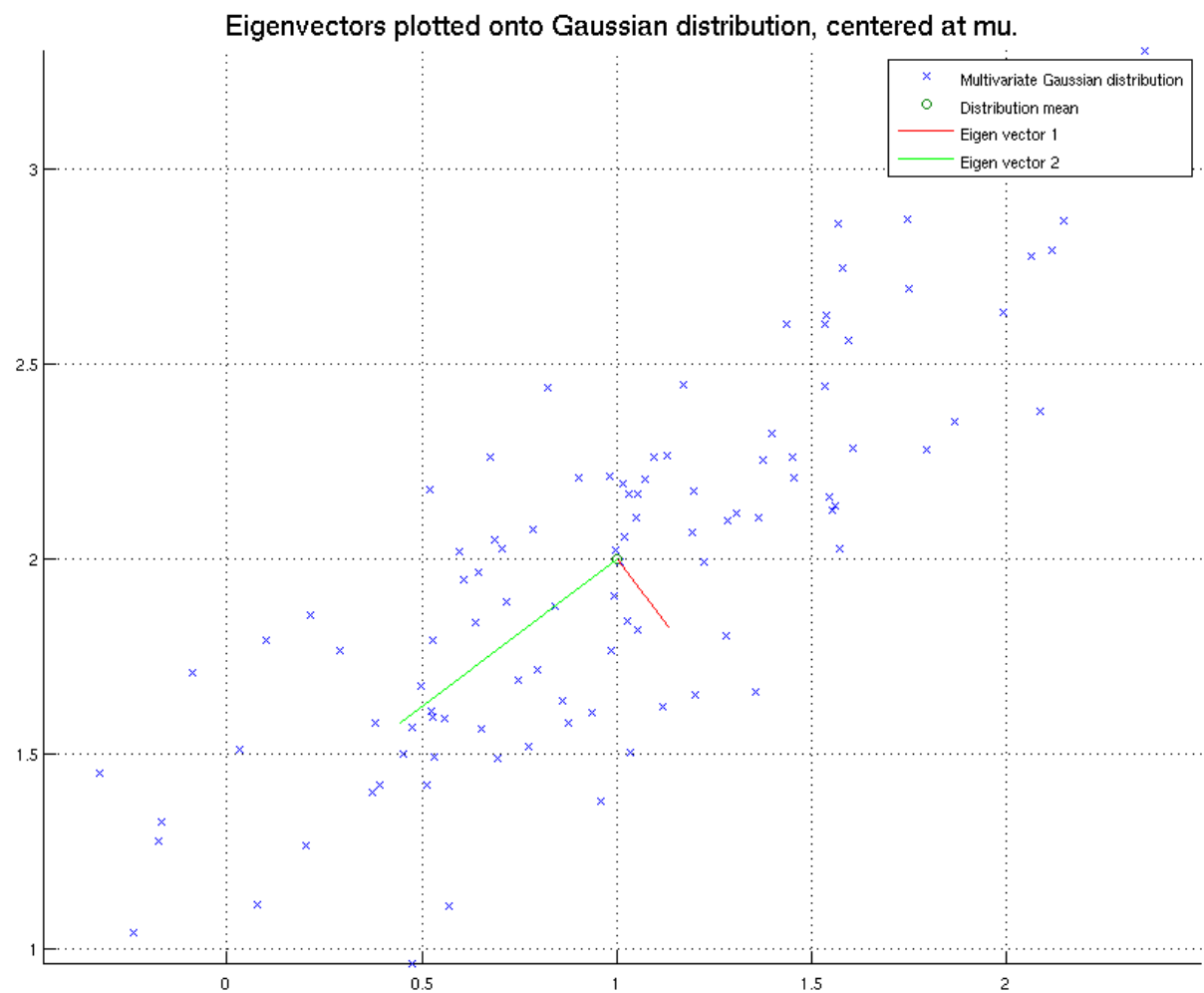


Figure 4: 100 points drawn from a 2-dimensional Multivariate gaussian distribution, plotted with the mean of the distribution, the value of  $\mu$  and the two eigenvectors centered in the distribution  $\mu$ .



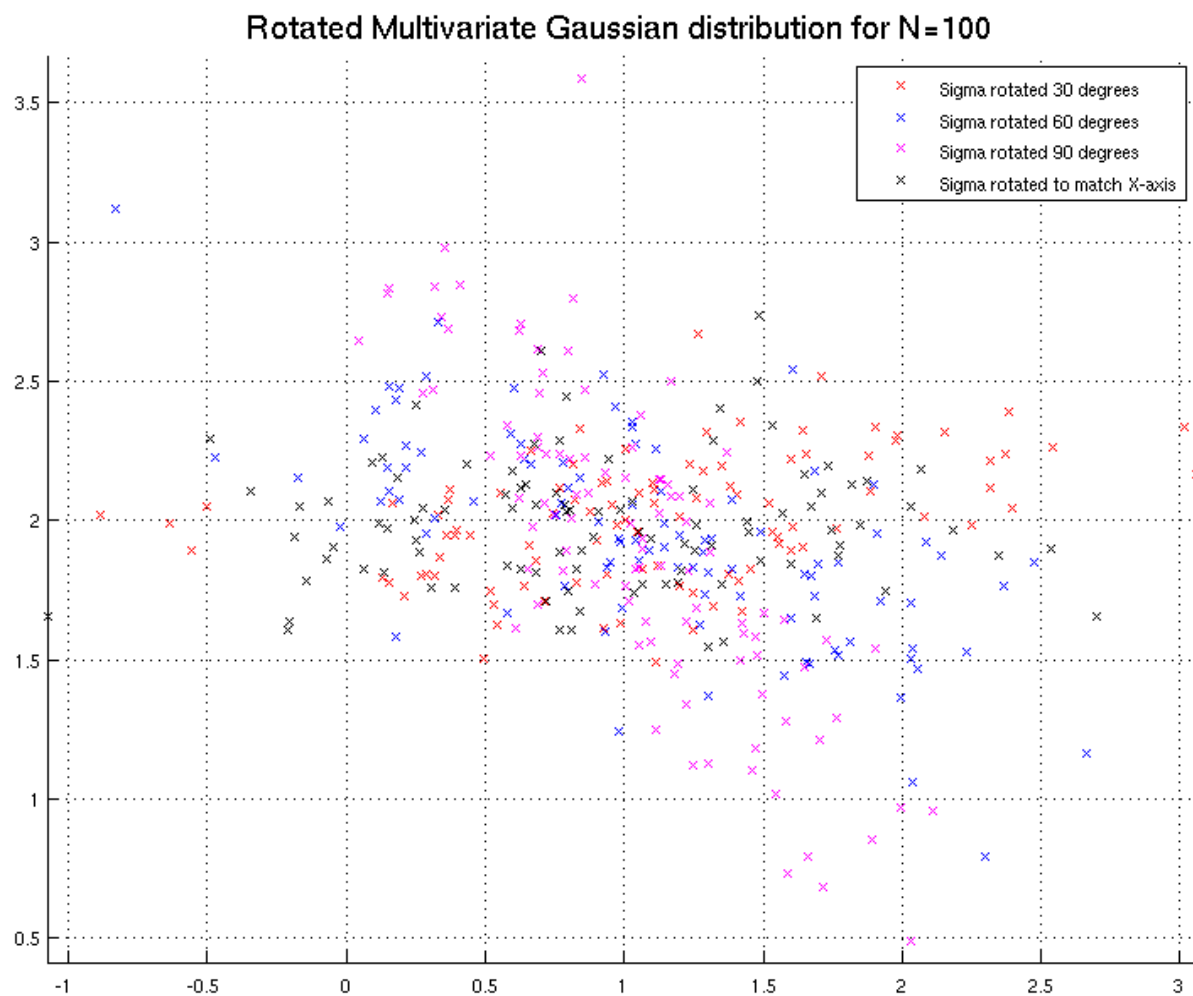


Figure 5: 100 points drawn from a 2-dimensional Multivariate gaussian distribution, rotated at 30, 60 and 90 degrees and lastly also aligned along the x-axis, all distributions in their own color.

## I.3

This is the make-up assignment.

Let:

$$\mathcal{N}(x|\mu_A, \sigma_A^2) = \frac{1}{\sqrt{2\pi\sigma_A^2}} e^{-\frac{1}{2\sigma_A^2}(x-\mu_A)^2}$$

$$\mathcal{N}(x|\mu_B, \sigma_B^2) = \frac{1}{\sqrt{2\pi\sigma_B^2}} e^{-\frac{1}{2\sigma_B^2}(x-\mu_B)^2}$$

be univariate Gaussian probability distribution functions.

We look at:

$$f(x) = \mathcal{N}(x|\mu_A, \sigma_A^2) \cdot \mathcal{N}(x|\mu_B, \sigma_B^2)$$

$$= \frac{1}{\sqrt{2\pi\sigma_A^2}} e^{-\frac{1}{2\sigma_A^2}(x-\mu_A)^2} \cdot \frac{1}{\sqrt{2\pi\sigma_B^2}} e^{-\frac{1}{2\sigma_B^2}(x-\mu_B)^2}$$

and want to show  $f(x)$  is an unnormalized Gaussian distribution.

As it is to be unnormalized we ignore the parts in front:

$$f(x) = C_1 \cdot e^{-\frac{1}{2\sigma_A^2}(x-\mu_A)^2} \cdot e^{-\frac{1}{2\sigma_B^2}(x-\mu_B)^2}.$$

In the following we alter this expression.

$$e^{-\frac{1}{2\sigma_A^2}(x-\mu_A)^2} \cdot e^{-\frac{1}{2\sigma_B^2}(x-\mu_B)^2} = e^{-\frac{1}{2\sigma_A^2}(x-\mu_A)^2 - \frac{1}{2\sigma_B^2}(x-\mu_B)^2}$$

We only look at the exponent.

$$-\frac{1}{2\sigma_A^2}(x-\mu_A)^2 - \frac{1}{2\sigma_B^2}(x-\mu_B)^2 = -\frac{(x-\mu_A)^2}{2\sigma_A^2} - \frac{(x-\mu_B)^2}{2\sigma_B^2}$$

$$= -\frac{2\sigma_B^2 \cdot (x-\mu_A)^2}{2\sigma_A^2 \cdot 2\sigma_B^2} - \frac{2\sigma_A^2 \cdot (x-\mu_B)^2}{2\sigma_A^2 \cdot 2\sigma_B^2}$$

$$= -\frac{2\sigma_B^2 \cdot (x-\mu_A)^2 + 2\sigma_A^2 \cdot (x-\mu_B)^2}{2\sigma_A^2 \cdot 2\sigma_B^2}$$

We now look at the numerator.

$$\begin{aligned}
& 2\sigma_B^2 \cdot (x - \mu_A)^2 + 2\sigma_A^2 \cdot (x - \mu_B)^2 \\
&= 2\sigma_B^2 \cdot x^2 + 2\sigma_B^2 \cdot \mu_A^2 - 2\sigma_B^2 \cdot 2x\mu_A + 2\sigma_A^2 \cdot x^2 + 2\sigma_A^2 \cdot \mu_B^2 - 2\sigma_A^2 \cdot 2x\mu_B \\
&= (2\sigma_B^2 + 2\sigma_A^2) \cdot x^2 + 2\sigma_B^2 \cdot \mu_A^2 + 2\sigma_A^2 \cdot \mu_B^2 - 2 \cdot (2\sigma_B^2\mu_A + 2\sigma_A^2\mu_B) \cdot x \\
&= (2\sigma_B^2 + 2\sigma_A^2) \cdot x^2 + 2\sigma_B^2 \cdot \mu_A^2 + 2\sigma_A^2 \cdot \mu_B^2 - \frac{(2\sigma_B^2 + 2\sigma_A^2)}{(2\sigma_B^2 + 2\sigma_A^2)} \cdot 2 \cdot (2\sigma_B^2\mu_A + 2\sigma_A^2\mu_B) \cdot x \\
&= (2\sigma_B^2 + 2\sigma_A^2) \cdot x^2 + 2\sigma_B^2 \cdot \mu_A^2 + 2\sigma_A^2 \cdot \mu_B^2 - 2(2\sigma_B^2 + 2\sigma_A^2) \cdot \frac{(2\sigma_B^2\mu_A + 2\sigma_A^2\mu_B)}{(2\sigma_B^2 + 2\sigma_A^2)} \cdot x \\
&= 2\sigma_B^2 \cdot \mu_A^2 + 2\sigma_A^2 \cdot \mu_B^2 - (2\sigma_B^2 + 2\sigma_A^2) \cdot \left( \frac{(2\sigma_B^2\mu_A + 2\sigma_A^2\mu_B)}{(2\sigma_B^2 + 2\sigma_A^2)} \right)^2 + (2\sigma_B^2 + 2\sigma_A^2) \cdot \left( x - \frac{(2\sigma_B^2\mu_A + 2\sigma_A^2\mu_B)}{(2\sigma_B^2 + 2\sigma_A^2)} \right)^2 \\
&= C_2 + (2\sigma_B^2 + 2\sigma_A^2) \cdot \left( x - \frac{(2\sigma_B^2\mu_A + 2\sigma_A^2\mu_B)}{(2\sigma_B^2 + 2\sigma_A^2)} \right)^2
\end{aligned}$$

Where  $C_2$  is independent of  $x$ . Setting:

$$\mu_{AB} = \frac{(2\sigma_B^2\mu_A + 2\sigma_A^2\mu_B)}{(2\sigma_B^2 + 2\sigma_A^2)}$$

we get:

$$C_2 + (2\sigma_B^2 + 2\sigma_A^2) \cdot (x - \mu_{AB})^2.$$

Now we reenter the denominator.

$$\begin{aligned}
& - \frac{C_2 + (2\sigma_B^2 + 2\sigma_A^2) \cdot (x - \mu_{AB})^2}{2\sigma_A^2 \cdot 2\sigma_B^2} \\
&= - \frac{C_2}{2\sigma_A^2 \cdot 2\sigma_B^2} - \frac{(2\sigma_B^2 + 2\sigma_A^2) \cdot (x - \mu_{AB})^2}{2\sigma_A^2 \cdot 2\sigma_B^2} \\
&= C_3 - \frac{1}{2} \cdot \frac{1}{\frac{\sigma_A^2 \cdot \sigma_B^2}{\sigma_B^2 + \sigma_A^2}} \cdot (x - \mu_{AB})^2
\end{aligned}$$

Setting:

$$\sigma_{AB}^2 = \frac{\sigma_A^2 \cdot \sigma_B^2}{\sigma_B^2 + \sigma_A^2}$$

we get:

$$C_3 - \frac{1}{2} \cdot \frac{1}{\sigma_{AB}^2} \cdot (x - \mu_{AB})^2.$$

We now reenter the base  $e$ .

$$\begin{aligned} e^{C_3 - \frac{1}{2\sigma_{AB}^2} \cdot (x - \mu_{AB})^2} &= e^{C_3} \cdot e^{-\frac{1}{2\sigma_{AB}^2} \cdot (x - \mu_{AB})^2} \\ &= C_4 \cdot e^{-\frac{1}{2\sigma_{AB}^2} \cdot (x - \mu_{AB})^2} \end{aligned}$$

And the ignored part:

$$\begin{aligned} f(x) &= C_1 \cdot C_4 \cdot e^{-\frac{1}{2\sigma_{AB}^2} \cdot (x - \mu_{AB})^2} \\ &= C_5 \cdot e^{-\frac{1}{2\sigma_{AB}^2} \cdot (x - \mu_{AB})^2}. \end{aligned}$$

$C_5$  can still be ignored, and we are now on the form we want, and we can see  $\mu = \mu_{AB}$  and  $\sigma = \sigma_{AB}$ .

## Old I.3

From here we have the old assignment which haven been altered.

Given:

$$\mu = \begin{pmatrix} \mu_a \\ \mu_b \\ \mu_c \end{pmatrix} \quad x = \begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix} \quad \Sigma = \begin{bmatrix} \Sigma_{aa} & \Sigma_{ab} & \Sigma_{ac} \\ \Sigma_{ba} & \Sigma_{bb} & \Sigma_{bc} \\ \Sigma_{ca} & \Sigma_{cb} & \Sigma_{cc} \end{bmatrix}$$

We wish to discover an expression for the conditional distribution  $p(x_a|x_b)$  in which  $x_c$  has been marginalized out.

We now use, that a vector of length  $i$  and a vector of length  $j$  can be seen as a vector of length  $k = i + j$ , and similarly with matrices.

Let:

$$\mu = \begin{pmatrix} \mu_d \\ \mu_c \end{pmatrix} \quad x = \begin{pmatrix} x_d \\ x_c \end{pmatrix} \quad \Sigma = \begin{bmatrix} \Sigma_{dd} & \Sigma_{dc} \\ \Sigma_{dc} & \Sigma_{cc} \end{bmatrix}$$

now we have from chapter 2.3.2 that:

$$\begin{aligned}\mathbb{E}[x_d] &= \Sigma_{dd} \\ &= \begin{bmatrix} \Sigma_{aa} & \Sigma_{ab} \\ \Sigma_{ba} & \Sigma_{bb} \end{bmatrix} \\ \text{cov}[x_d] &= \mu_d \\ &= \begin{pmatrix} \mu_a \\ \mu_b \end{pmatrix}\end{aligned}$$

when  $x_c$  has been marginalized out.

Now we have from chapter 2.3.1 for the conditional distribution  $p(x_a|x_b)$ :

$$\mu_{a|b} = \mu_a + \Sigma_{ab}\Sigma_{bb}^{-1}(x_b - \mu_b)\Sigma_{a|b} \qquad = \Sigma_{aa} - \Sigma_{ab}\Sigma_{bb}^{-1}\Sigma_{ba}.$$

Description	$K$ -value	Accuracy in %
Run on training data	1	100%
Run on test data	1	81.5%
Run on training data	3	86.0%
Run on test data	3	81.5%
Run on training data	5	83.0%
Run on test data	5	68.4%

Table 1: The results from I.4

## 1 I.4

### 1.1 I.4.1

The result of our KNN implementation for different  $k$ -values and datasets is shown in Table 1. The code to run this particular experiment is in `I_4_1.m`.

With  $K = 1$  and running against the training set, the accuracy is 100% since any entry will be matched against itself, and only itself. We also see a general loss of accuracy as  $K$  increases. This may be because the point gets matched up against a larger and larger set of the total points, and if there is inherent density clusters in the data then we risk going further and further out as  $K$  increases.

### 1.2 I.4.2

The code for this experiment is in `I_4_2.m`. It uses several auxiliary files found in the same directory. Given a set of possible  $k$  values ‘PossibleKValues’ the following pseudocode runs cross-validation to find the average loss experienced amongst each of the five folds of a cross-validation for each given  $k$  value, and then selects the best  $k$  as the one with the lowest average loss:

```

for  $k$  in PossibleKValues do
    subsets  $\leftarrow$  shuffleSplit(dataset,5)
    for  $cv = 1$  to 5 do
        test  $\leftarrow$  subsets[ $cv$ ]
        train  $\leftarrow$  subsets - test
        pred  $\leftarrow$  kNN( $k$ , train.X, train.y, test.X)
        loss[ $cv$ ]  $\leftarrow$   $1 - \frac{\text{pred} - \text{test.y}}{\text{length}(\text{pred})}$ 
    end for
    avgLoss[ $k$ ]  $\leftarrow$  mean(loss)
end for
bestK  $\leftarrow$  min(avgLoss)

```

▷ bucketJoiner function  
▷ bucketJoiner function

▷  $k$  for which avgLoss is lowest.

The `shuffleSplit` method splits a dataset into  $n$  randomized disjoint subsets, in this case  $n = 5$ . The `bucketJoiner` method joins one or more of these disjoint subsets into a single, larger subset by appending one onto the other. The  $k$ -value with the lowest average loss for our data was 5, with an accuracy of approximately 80%. The accuracy on the test data is 68,4%.

### 1.3 I.4.3

The code for this experiment can be found in `I_4_3.m`. The experiment is very similar to that of I.4.2. Before cross-validating, we normalize the data using the method found in `scale.m`.

The  $\mu$  values for the training data is  $(5.7560, 0.3017)$  and  $\sigma^2 = (0.6958, 0.0018)$ . Normalizing the training data gives  $\mu = (-0.3466 * 10^{-14}, -0.1823 * 10^{-14})$  and  $\sigma^2 = (1.0000, 1.0000)$ . After the normalization of the test data with the values found for the training data the test data have  $\mu = (0.2073, 0.43)$  and  $\sigma^2 = (1.0914, 1.2732)$ . Running the test from I.4.2 now gives  $K_{\text{best}} = 1$  and an accuracy of 78, 95% on the test data, and 100% accuracy on the training data. The last result is expected since when  $K = 1$  any entry will be closest to itself (the euclidian distance is 0.)

## References