

## Exercise Sheet 1

### Exercise 1: Estimating the Bayes Error (10 + 10 + 10 P)

The Bayes decision rule for the two classes classification problem results in the Bayes error

$$P(\text{error}) = \int P(\text{error} \mid \mathbf{x}) p(\mathbf{x}) d\mathbf{x},$$

where  $P(\text{error} \mid \mathbf{x}) = \min [P(\omega_1 \mid \mathbf{x}), P(\omega_2 \mid \mathbf{x})]$  is the probability of error for a particular input  $\mathbf{x}$ . Interestingly, while class posteriors  $P(\omega_1 \mid \mathbf{x})$  and  $P(\omega_2 \mid \mathbf{x})$  can often be expressed analytically and are integrable, the error function has discontinuities that prevent its analytical integration, and therefore, direct computation of the Bayes error.

- (a) Show that the full error can be upper-bounded as follows:

$$P(\text{error}) \leq \int \frac{2}{\frac{1}{P(\omega_1 \mid \mathbf{x})} + \frac{1}{P(\omega_2 \mid \mathbf{x})}} p(\mathbf{x}) d\mathbf{x}.$$

Note that the integrand is now continuous and corresponds to the harmonic mean of class posteriors weighted by  $p(\mathbf{x})$ .

- (b) Show using this result that for the univariate probability distributions

$$p(x \mid \omega_1) = \frac{\pi^{-1}}{1 + (x - \mu)^2} \quad \text{and} \quad p(x \mid \omega_2) = \frac{\pi^{-1}}{1 + (x + \mu)^2},$$

the Bayes error can be upper-bounded by:

$$P(\text{error}) \leq \frac{2 P(\omega_1) P(\omega_2)}{\sqrt{1 + 4\mu^2 P(\omega_1) P(\omega_2)}}$$

(Hint: you can use the identity  $\int \frac{1}{ax^2 + bx + c} dx = \frac{2\pi}{\sqrt{4ac - b^2}}$  for  $b^2 < 4ac$ .)

- (c) Explain how you would estimate the error if there was no upper-bounds that are both tight and analytically integrable. Discuss following two cases: (1) the data is low-dimensional and (2) the data is high-dimensional.

### Exercise 2: Bayes Decision Boundaries (15 + 15 P)

One might speculate that, in some cases, the generated data  $p(x \mid \omega_1)$  and  $p(x \mid \omega_2)$  is of no use to improve the accuracy of a classifier, in which case one should only rely on prior class probabilities  $P(\omega_1)$  and  $P(\omega_2)$  assumed here to be strictly positive.

For the first part of this exercise, we assume that the data for each class is generated by the univariate Laplacian probability distributions:

$$p(x \mid \omega_1) = \frac{1}{2\sigma} \exp\left(-\frac{|x - \mu|}{\sigma}\right) \quad \text{and} \quad p(x \mid \omega_2) = \frac{1}{2\sigma} \exp\left(-\frac{|x + \mu|}{\sigma}\right).$$

where  $\mu, \sigma > 0$ .

- (a) Determine for which values of  $P(\omega_1), P(\omega_2), \mu, \sigma$  the optimal decision is to always predict the first class (i.e. under which conditions  $P(\text{error} \mid x) = P(\omega_2 \mid x) \quad \forall x \in \mathbb{R}$ ).
- (b) Repeat the exercise for the case where the data for each class is generated by the univariate Gaussian probability distributions:

$$p(x \mid \omega_1) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \quad \text{and} \quad p(x \mid \omega_2) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x + \mu)^2}{2\sigma^2}\right).$$

where  $\mu, \sigma > 0$ .

### Exercise 3: Programming (40 P)

Download the programming files on ISIS and follow the instructions.