

## 0 Instructions

Homework is due Thursday, February 6, 2024 at 23:59pm Central Time. Please refer to <https://courses.grainger.illinois.edu/cs446/sp2024/homework/hw/index.html> for course policy on homeworks and submission instructions.

## 1 Short answer: 10pts

Each question is worth 2 points. One-sentence explanations are allowed but not necessary for full credit.

1. A (1-)nearest neighbour model is trained on a dataset  $\mathcal{D} = \{(x^{(i)}, y^{(i)})\}_{i=1}^N$  where  $x^{(i)} \in \mathbf{R}^d \forall i$ . That is, there are  $N$  training images, each of which is dimension  $d$ . It is then used to evaluate  $M$  test images. What is the time complexity of the test-time evaluation? Use big-O notation.
2. Consider two different  $k$ -nearest neighbor models: one has  $k = 1$  and one with  $k = 10$ . In general, which would you expect to expect to have a “smoother” decision boundary?
3. Let  $g$  be the logical OR function, defined on the feature space  $\{+1, -1\}^2$ , which maps  $g(+1, +1) = +1, g(-1, +1) = +1, g(+1, -1) = +1, g(-1, -1) = -1$ . Given a linear classifier  $h(x) = \text{sign}(\mathbf{w} \cdot \mathbf{x} + b)$ , give a valid  $(\mathbf{w}, b)$  pair that matches ground truth  $g$ . Let  $\text{sign}(z) = +1$  for  $z \geq 0$  and  $-1$  otherwise.
4. For real matrix  $A \in \mathbb{R}^{n \times m}$ , what relationship does the largest singular value of  $A$  have with the largest eigenvalue of  $A^\top A$ ?
5. As mentioned in lecture, image data does not normally satisfy the Naive Bayes assumption. Give one additional example of a real-world situation in which the Naive Bayes assumption is violated.

## 2 Linear Regression: 10pts

Consider a data matrix  $X \in \mathbb{R}^{n \times d}$  with rows  $(\mathbf{x}_i)_{i=1}^n$ . Assume that  $d > n$  and that  $X$  is full-rank; that is,  $\text{rank}(X) = n$ .

1. (5pts) Show that there exists a  $\mathbf{w}$  such that the empirical risk with squared loss is zero, i.e., that  $X\mathbf{w} = \mathbf{y}$ .
2. (2pts) Let the SVD of  $X$  be  $X = U\Sigma V^\top$ . What is the rank of  $\Sigma$ ?
3. (3pts) Show that  $XX^\top$  is invertible.

### 3 SVM: 10 pts

1. (2pts) Recall the dual of hard-margin SVM for binary classification:

$$\max_{\boldsymbol{\alpha}} \sum_{i=1}^n \alpha_i - \frac{1}{2} \sum_{i,j=1}^n \alpha_i \alpha_j y_i y_j \mathbf{x}_i^\top \mathbf{x}_j : \boldsymbol{\alpha} \in \mathbb{R}^n, \boldsymbol{\alpha} \geq 0$$

What is the smallest number of support vectors for a  $d$ -dimensional dataset  $\mathcal{D} = \{(\mathbf{x}_i, y_i)\}_{i=1}^{10,000}$ ? In other words,  $\mathbf{x}_i \in \mathbb{R}^d \forall i \in [n]$ . Assume that  $\mathcal{D}$  is linearly separable and that there exists at least one point in each class.

2. (3pts) Recall from lecture that for any datapoint  $(\mathbf{x}_i, y_i)$ , if  $\alpha_i > 0$ , then  $\mathbf{x}_i$  is a support vector. We will complete the definition of support vector to be *any point that lies on the margin*; in other words, a given point  $(\mathbf{x}_i, y_i)$  is a support vector if and only if  $y_i(\mathbf{w}^*)^\top \mathbf{x}_i = 1$ .

Now, let an optimal solution to the dual on our dataset  $\mathcal{D}$  be  $\boldsymbol{\alpha} = [10, 2, 3, 0, \dots, 0]$  (omitted elements are all 0). What is the smallest possible and largest possible number of support vectors in  $\mathcal{D}$ ?

**Hint:** A solution to the dual might not be unique. Is it possible for a point to contribute to the optimal  $\mathbf{w}^*$  for one solution  $\boldsymbol{\alpha}$ , but have 0 contribution/weight in a different solution  $\boldsymbol{\alpha}'$ ? Is this point a support vector?

3. Recall the XOR problem. In this question, we want to model the function  $g_{XOR} : \{-1, 1\}^2 \rightarrow \{-1, 1\}$ :

$$\begin{aligned} g_{XOR}(-1, -1) &= g_{XOR}(1, 1) = 1 \\ g_{XOR}(1, -1) &= g_{XOR}(-1, 1) = -1 \end{aligned}$$

To solve this problem, we need a nonlinear mapping. Consider the following kernel:

$$k(\mathbf{x}, \mathbf{z}) = (\mathbf{x}^\top \mathbf{z} + 1)^2$$

- (a) (3pts) Write out a feature mapping  $\phi : \mathbb{R}^2 \rightarrow \mathbb{R}^d$  that induces this kernel. In other words, what is one  $\phi$  that satisfies  $\phi(\mathbf{x})^\top \phi(\mathbf{z}) = k(\mathbf{x}, \mathbf{z})$ ?
- (b) (2pts) Find a solution  $\mathbf{w}$  such that  $h(\mathbf{z}) = \text{sign}(\mathbf{w}^\top \phi(\mathbf{z})) = g_{XOR}(\mathbf{z})$

## 4 Gaussian Naive Bayes: 15pts

Recall that the Bayes Classifier is

$$h(\mathbf{x}) = \underset{y}{\operatorname{argmax}} P(y|\mathbf{x})$$

We will work with binary classification:  $y_i \in \{-1, +1\} \forall i \in [n]$ . The feature vectors are now continuous:  $\mathbf{x} \in \mathbb{R}^d$ .

1. (5pts) Assume that we have a prior  $P(y = +1) = p$  for some  $p \in (0, 1)$ .

Show that the predictor  $P(y = +1|\mathbf{x})$  can be written can be written  $\frac{1}{1 + \exp(\log \frac{A}{B})}$

where  $A, B$  are expressions in terms of  $p, P(\mathbf{x}|y = +1), P(\mathbf{x}|y = -1)$ .

2. (8pts) Consider a Gaussian Naive Bayes model. Let  $x_j$  be the  $j$ th element of  $\mathbf{x}$ . Let the data be generated as follows for  $\boldsymbol{\mu}_+, \boldsymbol{\mu}_- \in \mathbb{R}^d$  and  $I \in \mathbb{R}^{d \times d}$  the identity matrix:

$$P(\mathbf{x}|y = +1) = \mathcal{N}(\boldsymbol{\mu}_+, I), \quad P(\mathbf{x}|y = -1) = \mathcal{N}(\boldsymbol{\mu}_-, I)$$

For example, the positive class has distribution

$$P(x_j|y = +1) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(x_j - \mu_{+,j})^2}{2}\right)$$

Show that the expression from the previous part,  $\log \frac{A}{B}$ , can be written in the form  $\mathbf{w}^\top \mathbf{x} + b$ , where  $\mathbf{w}$  and  $b$  are expressions in terms of  $p, \boldsymbol{\mu}_+, \boldsymbol{\mu}_-$ . Identify assumptions and definitions used in your derivation.

3. (2pts) Write a single expression for  $P(y|\mathbf{x})$  as a function of  $y, \mathbf{x}, \mathbf{w}, b$ .

## 5 Linear regression: 14pts + 1pt

Recall that the empirical risk in the linear regression method is defined as

$$\mathcal{R}(w) := \frac{1}{2n} \sum_{i=1}^n (w^\top x_i - y_i)^2$$

where  $x_i \in \mathbb{R}^d$  is a data point and  $y_i$  is an associated label.

1. (10.5pts) **Implement** the linear regression method using gradient descent in `linear_gd(X, Y, lrate, num_iter)` function in `hw1.py`. You are given a training set `X` as input and training labels `Y` as input along with a learning rate `lrate` and maximum number

- of iterations `num_iter`. Using gradient descent find parameters  $w$  that minimize the empirical risk  $\mathcal{R}(w)$ . One iteration is equivalent to one full data gradient update step. Use a learning rate of `lr` and only run for `num_iter` iterations. Use  $w = 0$  as your initial parameters, and return your parameters  $w$  as output.
2. (3.5pts) **Implement** linear regression by setting the gradient to zero and solving for the variables, in `linear_normal(X,Y)` function in `hw1.py`. You are given a training set `X` as input and training labels `Y` as input. Return your parameters  $w$  as output.
  3. (1pt) Implement the `plot_linear()` function in `hw1.py`. Use the provided function `utils.load_reg_data()` to generate a training set `X` and training labels `Y`. Plot the curve generated by `linear_normal()` along with the points from the data set. Return the plot as output. **Include the plot in your written submission.**