

# Statistical Learning

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## 1 Introduction

## 2 Bibliography

# Preliminary note

The material in these slides is strongly based on [1]. When other materials are used, they are cited accordingly.

Mathematical notation follows as good as it can a [good practices proposal](<https://ctan.math.utah.edu/ctan/tex-archive/macros/latex/contrib/mlmath/mlmath.pdf>) from the Beijing Academy of Artificial Intelligence.

# How is data analyzed and used?

**Statistical learning** interpret the model and quantify the uncertainty of the data.

**Machine learning** (or *data mining* making predictions using large scale data.

The goals of modelling data are:

- to predict data, based on existing one;
- to discover unusual or interesting patterns in data.

# Tools to model data

**Function approximation** Model data with approximate and simple functions or maps.

**Optimization** Given a set of feasible mathematical models to the data, we may need to find the optimal one by fitting or calibrating a function to observed data.

**Probability and Statistics** Probability theory and statistical inference provides ways to quantify the uncertainty inherent in making predictions based on observed data.

# Some basic notation I

Given an input or *feature* vector  $\mathbf{x}$ , ML aims at predicting an output or *response* variable vector  $\mathbf{y}$ . In particular, we search for a mathematical *prediction function*  $g$  such that we can *guess* an approximation to  $\mathbf{y}$ ,  $\hat{\mathbf{y}}$ :

$$\begin{aligned} g: \mathcal{X} &\rightarrow \mathcal{Y} \\ \mathbf{x} &\mapsto \hat{\mathbf{y}} = g(\mathbf{x}) \end{aligned}$$

## Definition

Dataset  $S = \{\mathbf{z}_i\}_{i=1}^n = \{(\mathbf{x}_i, \mathbf{y}_i)\}_{i=1}^n$  is sampled from a distribution  $\mathcal{D}$  over a domain  $\mathcal{Z} = \mathcal{X} \times \mathcal{Y}$ .

$\mathcal{X}$  is the instance domain (a set),  $\mathcal{Y}$  is the label domain (a set), and  $\mathcal{Z} = \mathcal{X} \times \mathcal{Y}$  is the example domain (a set).

# Some basic notation II

Usually,  $\mathcal{X}$  is a subset of  $\mathbb{R}^d$  and  $\mathcal{Y}$  is a subset of  $\mathbb{R}^{d_o}$ , where  $d$  is the input dimension,  $d_o$  is the output dimension.

$n = \#S$  is the number of samples. Without specification,  $S$  and  $n$  are for the training set.

- In *regression* problems,  $\mathbf{y}$  is a vector of real values.
- In *classification* problems,  $\mathbf{y}$  values lie within a finite set of  $c$  categories:  $y \in \{0, 1, \dots, c - 1\}$ .

## Definition

A hypothesis space is denoted by  $\mathcal{H}$ . A hypothesis function is denoted by  $f_{\theta}(\mathbf{x}) \in \mathcal{H}$  or  $f(\mathbf{x}; \theta) \in \mathcal{H}$  with  $f_{\theta} : \mathcal{X} \rightarrow \mathcal{Y}$ .

$\theta$  denotes the set of parameters of  $f_{\theta}$ .

If there exists a target function, it is denoted by  $f^*$  or  $f : \mathcal{X} \rightarrow \mathcal{Y}$  satisfying  $y_i = f^*(\mathbf{x}_i)$  for  $i = 1, \dots, n$ .

## Some basic notation III

A loss function, denoted by  $\ell : \mathcal{H} \times \mathcal{Z} \rightarrow \mathbb{R}_+ := [0, +\infty)$ , measures the difference (or error) between a predicted label and a true label, e.g.,  $L^2$  loss:

$$\ell(f_\theta, \mathbf{z}) = \frac{1}{2}(f_\theta(\mathbf{x}) - \mathbf{y})^2,$$

where  $\mathbf{z} = (\mathbf{x}, \mathbf{y})$ .  $\ell(f_\theta, \mathbf{z})$  can also be written as

$$\ell(f_\theta(\mathbf{x}), \mathbf{y})$$

for convenience.

(In the case of a classification,  $\ell(f_\theta, \mathbf{y}) = \mathbb{1}\{y \neq \hat{\mathbf{y}}\}$ )

We will see other useful loss functions (cross entropy or *hinge* loss functions) later in this course.

It is unlikely that a mathematical function  $g \equiv f_\theta : \mathcal{X} \rightarrow \mathcal{Y}$  would be able to make accurate predictions of all possible pairs  $\mathcal{Z} = \mathcal{X} \times \mathcal{Y}$ .



## Some basic notation IV

So, we use a probabilistic approach here to empirical risk or training loss for a set  $S = \{(\mathbf{x}_i, \mathbf{y}_i)\}_{i=1}^n$  is denoted by  $L_S(\boldsymbol{\theta})$  or  $L_n(\boldsymbol{\theta})$  or  $R_n(\boldsymbol{\theta})$  or  $R_S(\boldsymbol{\theta})$ ,

$$L_S(\boldsymbol{\theta}) = \frac{1}{n} \sum_{i=1}^n \ell(f_{\boldsymbol{\theta}}(\mathbf{x}_i), \mathbf{y}_i). \quad (1)$$

The population risk or expected loss is denoted by  $L_{\mathcal{D}}(\boldsymbol{\theta})$  or  $R_{\mathcal{D}}(\boldsymbol{\theta})$

$$L_{\mathcal{D}}(\boldsymbol{\theta}) = \mathbb{E}_{\mathcal{D}} \ell(f_{\boldsymbol{\theta}}(\mathbf{z}), \mathbf{y}), \quad (2)$$

where  $\mathbf{z} = (\mathbf{x}, \mathbf{y})$  follows the distribution  $\mathcal{D}$ .

(In the case of a classification, we denote  $L_{\mathcal{D}}(g) \equiv L_{\mathcal{D}}(\boldsymbol{\theta}) = \mathbb{P}_{\mathcal{D}}[f_{\boldsymbol{\theta}}(\mathbf{x}) \neq \mathbf{y}]$  and we say that  $g$  is a classifier.)

Because we are interested in minimizing the risk in our prediction, we are looking for the best possible  $g^* := \operatorname{argmin}_g \mathbb{E}_{\mathcal{D}} \ell(f_{\boldsymbol{\theta}}(\mathbf{x}), \mathbf{y})$

# Some basic notation V

(In classification, we look for  $g^*(\mathbf{x}) = \underset{y \in \{0,1,\dots,c-1\}}{\operatorname{argmax}} \mathbb{P}[Y = y | \mathbf{X} = \mathbf{x}]$ .)

## Theorem

*For the squared-error loss  $\ell(y, \hat{y}) = (y - \hat{y})^2$ , the optimal prediction function  $g^*$  is equal to the conditional expectation of  $Y$  given  $\mathbf{X} = \mathbf{x}$ .*

which leads to write the random response  $Y$  as:

$$Y = g^*(\mathbf{x}) + \varepsilon(\mathbf{x})$$

Note that such random deviation satisfies  $\mathbb{E}\varepsilon(\mathbf{x}) = 0$



Dirk P. Kroese, Zdravko Botev, Thomas Taimre, and Radislav Vaisman.

*Data Science and Machine Learning: Mathematical and Statistical Methods.*

Machine Learning & Pattern Recognition. Chapman & Hall/CRC, 2020.