Lectures on Data Science and Engineering
Lecture 2

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Introduction

In the previous lecture we learned what is the Training error (Empirical Risk) and the Generalization Error (True Risk) and how to compute it for a model h.

Recall: We are given a dataset $\mathcal{S}$ of n labeled examples and the Empirical Risk is

$$L_{\mathcal{S}}(h) = \frac{1}{n}\sum_{i=1}^{n} \ell(h(\mathbf{x}_i), y_i)),$$

which is averaging the loss over our training set. We hope that this will be a good approximation to the **True risk** of a model h, denoted by $L_D(h)$ as follows:

$$L_D(h) = \mathrm{E}_{\mathbf{x}\sim D}[\ell(h(\mathbf{x}), h_T(\mathbf{x})].$$

For any given model we can compute its training error. The challenge of training is to find the *best possible model*. In other words, we would ideally like to search over all possible models (*i.e.* search over all possible python functions that take the features $\mathbf{x}$ and produce a label y) to choose the one with the smallest empirical risk on the training set $\mathcal{S}$. This is called Empirical Risk Minimization (ERM):

$$\min_h L_S(h) = \min_h \frac{1}{n}\sum_{i=1}^{n} \ell(h_1(\mathbf{x}_i), y_i)).$$

where we are searching over all models to find the one that minimizes the loss.
Let's remember our dataset $\mathcal{S}$:

Lets use the zero-one loss ℓ_{01} which takes as input a prediction $\hat{y}$ and a true value y and charges 1 when the prediction is wrong and zero otherwise:

$$\ell_{01}(\hat{y}, y) = \begin{cases} 0 & \text{if } \hat{y} = y, \\ 1 & \text{otherwise.} \end{cases}$$

	height	width	y=exploded?
chip 1	0.8	0.8	1
chip 2	0.3	0.25	0
chip 3	0.2	0.8	0
chip 4	0.3	0.7	0
chip 5	0.9	0.7	1

Table 1: Your dataset $\mathcal{S}$. There is a special column (called y) that we are trying to predict using the other columns called features. Every row corresponds to one labeled nano-chip. The number of examples (aka Samples) is usually denoted by n and the number of features by p. In this example $n = 4$ and $p = 2$.

Exercise 1

How small can you make the training error for this dataset $\mathcal{S}$ for the zero-one loss ℓ_{01}? You can use any model h you want.

Think about the previous exercise before continuing.

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The problem is that we can always make the training error zero. One way to do this is by a model h that **memorizes** the dataset $\mathcal{S}$ and produces labels as follows:

Stupid Memorization Model h_m

- For a given input $\mathbf{x}$, if the same feature vector $\mathbf{x}$is in the training set, output the training label as a prediction: $h_m(\mathbf{x}) = y$.
- For a given input $\mathbf{x}$that is not in the training set, make the prediction $h_m(\mathbf{x}) = 0$

This model h_m achieves zero empirical loss but is a terrible model that will always predict 0 unless it has seen the example before. Using the framework of the previous lecture you can compute the true risk of h_m (for the D and true labeling function h_T given in Lect.1) and you will find that it is 1, i.e. the worst possible risk. This model has simply memorized the training set but has no predictive power: This is an example of **overfitting**.

1 How to avoid overfitting: Inductive Bias

The way we usually avoid overfitting is through **hope**: the hope that the universe is simple. Instead of minimizing the empirical risk over *all possible models* we limit our search within *simple* models. We critically assume here that the true labeling function h_T is also simple and hence our search over simple models will find it, or find a model close to it[1].

1.1 Example: ERM over Stumps

In this example we will search over all decision stumps that look only at the variable *width*: Lets consider decision stumps h_θ that lebel points as follows:

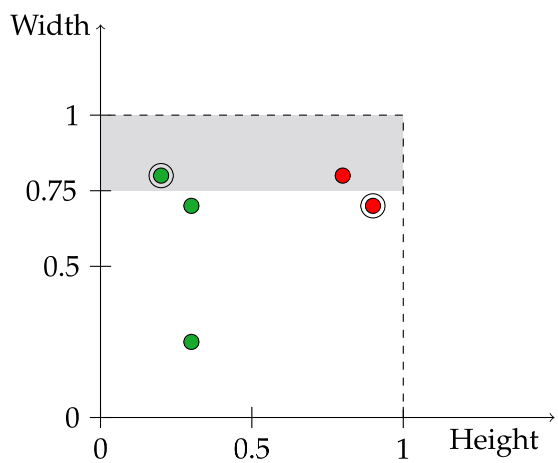
$$h_\theta(w, h) = \begin{cases} 1 & \text{if } w \geq \theta, \\ 0 & \text{otherwise.} \end{cases}$$

This is now a family of models $\mathcal{H}$. This is called a *hypothesis class* and this particular one is quite simple and is parametrized by one scalar parameter θ, the threshold we use.

We will now perform ERM over this hypothesis class:

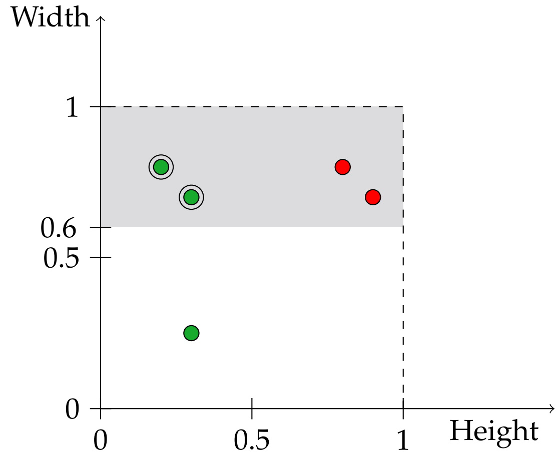
$$\min_{h \in \mathcal{H}} L_S(h_\theta) = \min_{\theta \in [0,1]} L_S(h_\theta).$$

Lets draw the decision region for h_θ when $\theta = 0.75$:



For $\theta = 0.75$ the model is misclassifying two points shown circled. So the emprical risk is $L_S(h_{0.75}) = \frac{1}{5}2$.
If we choose $\theta = 0.6$ we have the decision region:

[1] This is all formalized in the field of learning theory, where complexity is measured by the concept of VC dimension and its extensions.



For $\theta = 0.6$ the model is misclassifying again two points shown circled. So the emprical risk is the same: $L_S(h_{0.75}) = \frac{1}{5}2$.

You can see that for this dataset, there is no decision stump on the feature *width* that will misclassify fewer than 2 points. So $\theta* = 0.6$ or $\theta* = 0.7$ can be selected as an ERM optimum. If instead one uses a decision stump on the variable height, thresholding height on 0.5 will produce zero training error.

Exercise 2

- Think of an algorithm for training binary decision stump models.
- What is the running time in terms of the number of samples n and number of features p?

Exercise 3

Assume a data generation model as in Lecture 1:
• $D \sim$ Uniform$[0,1]x[0,1]$. In words, the weight and the height of the nano-chips are selected randomly uniformly and independently in $[0,1]$.
Assume the true labeling function to be:

$$h_T(w,h) = \begin{cases} 1 & \text{if } (w-1)^2 + (h-1)^2 \leq \frac{1}{4}, \\ 0 & \text{otherwise.} \end{cases}$$

This function will label nanochips as $h_T = 1$ (*exploding*) if their weight,height combination is within distance $1/2$ from the point $[1,1]$. We are using 0-1 loss throughout.
• Perform true risk minimization to find $\theta*$ for stumps on *width*.
• Perform true risk minimization over either *width* or *height*. What is the lowest possible true risk?