

I2ML :: BASICS

Data

$\mathcal{X} \subseteq \mathbb{R}^p$: p -dimensional **feature space** / input space
Usually we assume categorical features to be numerically encoded.

\mathcal{Y} : **target space**
e.g.: $\mathcal{Y} = \mathbb{R}$ for regression, $\mathcal{Y} = \{0, 1\}$ or $\mathcal{Y} = \{-1, +1\}$ for binary classification, $\mathcal{Y} = \{1, \dots, g\}$ for multi-class classification with g classes

$\mathbf{x} = (x_1, \dots, x_p)^T \in \mathcal{X}$: **feature vector** / covariate vector

$y \in \mathcal{Y}$: **target variable** / output variable
Concrete samples are called labels

$(\mathbf{x}^{(i)}, y^{(i)}) \in \mathcal{X} \times \mathcal{Y}$: i -th **observation** / sample / instance / example

$\mathbb{D} = \bigcup_{n \in \mathbb{N}} (\mathcal{X} \times \mathcal{Y})^n$: **set of all finite data sets**

$\mathbb{D}_n = (\mathcal{X} \times \mathcal{Y})^n \subseteq \mathbb{D}$: **set of all finite data sets of size n**

$\mathcal{D} = ((\mathbf{x}^{(1)}, y^{(1)}), \dots, (\mathbf{x}^{(n)}, y^{(n)})) \in \mathbb{D}_n$: **data set** of size n . An n -tuple, a family indexed by $\{1, \dots, n\}$. We use \mathcal{D}_n to emphasize its size.

$\mathcal{D}_{\text{train}}, \mathcal{D}_{\text{test}} \subseteq \mathcal{D}$: **data sets for training and testing**
Often: $\mathcal{D} = \mathcal{D}_{\text{train}} \dot{\cup} \mathcal{D}_{\text{test}}$

\mathbb{P}_{xy} : **joint probability distribution on $\mathcal{X} \times \mathcal{Y}$**

Classification

$o_k(y) = \mathbb{I}(y = k) \in \{0, 1\}$: multiclass one-hot encoding, if y is class k
We write $\mathbf{o}(y)$ for the g -length encoding vector and $o_k^{(i)} = o_k(y^{(i)})$

$\pi_k = \mathbb{P}(y = k)$: **prior probability** for class k
In case of binary labels we might abbreviate: $\pi = \mathbb{P}(y = 1)$.

Model and Learner

Model / Hypothesis: $f : \mathcal{X} \rightarrow \mathbb{R}^g$ maps features to predictions, often parametrized by $\boldsymbol{\theta} \in \Theta$ (then we write $f_{\boldsymbol{\theta}}(\mathbf{x})$ or $f(\mathbf{x}|\boldsymbol{\theta})$).

$\Theta \subseteq \mathbb{R}^d$: **parameter space**

$\boldsymbol{\theta} = (\theta_1, \theta_2, \dots, \theta_d) \in \Theta$: model **parameter** vector
Some models may traditionally use different symbols.

$\mathcal{H} = \{f : \mathcal{X} \rightarrow \mathbb{R}^g \mid f \text{ belongs to a certain functional family} \}$:
Hypothesis space – set of functions to which we restrict learning

Learner / Inducer $\mathcal{I} : \mathbb{D} \times \boldsymbol{\Lambda} \rightarrow \mathcal{H}$ takes a training set $\mathcal{D}_{\text{train}} \in \mathbb{D}$, produces model $f : \mathcal{X} \rightarrow \mathbb{R}^g$, with hyperparam. configuration $\boldsymbol{\lambda} \in \boldsymbol{\Lambda}$.
We also write $\mathcal{I} : \mathbb{D} \times \boldsymbol{\Lambda} \rightarrow \Theta$ or $\mathcal{I}_{\boldsymbol{\lambda}} : \mathbb{D} \rightarrow \Theta$

$\boldsymbol{\Lambda} = \boldsymbol{\Lambda}_1 \times \boldsymbol{\Lambda}_2 \times \dots \times \boldsymbol{\Lambda}_{\ell} \subseteq \mathbb{R}^{\ell}$: **hyperparameter space**
 $\boldsymbol{\Lambda}_j$ are usually bounded real or integer intervals or a finite categorical set

$\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \dots, \lambda_{\ell}) \in \boldsymbol{\Lambda}$: **hyperparameter configuration**

$\epsilon = y - f(\mathbf{x})$ or $\epsilon^{(i)} = y^{(i)} - f(\mathbf{x}^{(i)})$: (i -th) **residual** in regression

Classification

$\pi_k(\mathbf{x}) : \mathcal{X} \rightarrow [0, 1]$ **probability prediction** for class k , approximates $\mathbb{P}(y = k \mid \mathbf{x})$; for binary we abbreviate with $\pi(\mathbf{x})$ for $\mathbb{P}(y = 1 \mid \mathbf{x})$.

$f_k(\mathbf{x}) : \mathcal{X} \rightarrow \mathbb{R}$: **scoring** / discriminant **function** for class k ;
for binary we use $f(\mathbf{x}) = f_1(\mathbf{x}) - f_2(\mathbf{x})$

$h(\mathbf{x}) : \mathcal{X} \rightarrow \mathcal{Y}$: **hard label function**;
Typically created by $h(\mathbf{x}) = \arg \max_{k \in \{1, \dots, g\}} f_k(\mathbf{x})$ or $h(\mathbf{x}) = \arg \max_{k \in \{1, \dots, g\}} \pi_k(\mathbf{x})$

$y f(\mathbf{x})$ or $y^{(i)} f(\mathbf{x}^{(i)})$: **margin** for (i -th) observation in binary classification

$\hat{y}, \hat{f}, \hat{h}, \hat{\pi}_k(\mathbf{x}), \hat{\pi}(\mathbf{x})$ and $\hat{\boldsymbol{\theta}}$
The hat symbol denotes **learned** functions and parameters.

Loss, Risk and ERM

$L : \mathcal{Y} \times \mathbb{R}^g \rightarrow \mathbb{R}_0^+$: **loss function**: Quantifies "quality" $L(y, f(\mathbf{x}))$ of prediction $f(\mathbf{x})$ (or $L(y, \pi(\mathbf{x}))$ of prediction $\pi(\mathbf{x})$) for true y .

$\mathcal{R}_{\text{emp}} : \mathcal{H} \rightarrow \mathbb{R}$: **(theoretical) risk** ; $\mathcal{R}(f) = \mathbb{E}_{((\mathbf{x}, y) \sim \mathbb{P}_{xy})}[L(y, f(\mathbf{x}))]$

$\mathcal{R}_{\text{emp}} : \mathcal{H} \rightarrow \mathbb{R}$: **empirical risk** ; $\mathcal{R}_{\text{emp}}(f) = \sum_{i=1}^n L(y^{(i)}, f(\mathbf{x}^{(i)}))$

Since f is usually defined by **parameters $\boldsymbol{\theta}$** , we also write:
 $\mathcal{R}_{\text{emp}} : \Theta \rightarrow \mathbb{R}$; $\mathcal{R}_{\text{emp}}(\boldsymbol{\theta}) = \sum_{i=1}^n L(y^{(i)}, f(\mathbf{x}^{(i)} \mid \boldsymbol{\theta}))$

Empirical risk minimization (ERM): $\hat{\boldsymbol{\theta}} \in \arg \min_{\boldsymbol{\theta} \in \Theta} \mathcal{R}_{\text{emp}}(\boldsymbol{\theta})$

Regression Losses

L2 loss / squared error:

- $L(y, f(\mathbf{x})) = (y - f(\mathbf{x}))^2$ or $L(y, f(\mathbf{x})) = 0.5(y - f(\mathbf{x}))^2$
- Convex and differentiable, non-robust against outliers
- Optimal constant model: $\hat{f}(\mathbf{x}) = \frac{1}{n} \sum_{i=1}^n y^{(i)} = \bar{y}$
- Optimal model over \mathbb{P}_{xy} for unrestricted \mathcal{H} : $\hat{f}(\mathbf{x}) = \mathbb{E}[y|\mathbf{x}]$

L1 loss / absolute error:

- $L(y, f(\mathbf{x})) = |y - f(\mathbf{x})|$
- Convex and more robust, non-differentiable
- Optimal constant model: $\hat{f}(\mathbf{x}) = \text{med}(y^{(1)}, \dots, y^{(n)})$
- Optimal model over \mathbb{P}_{xy} for unrestricted \mathcal{H} : $\hat{f}(\mathbf{x}) = \text{med}[y|\mathbf{x}]$

Classification Losses

0-1-loss (binary case)
 $L(y, h(\mathbf{x})) = \mathbb{I}(y \neq h(\mathbf{x}))$
 $L(y, f(\mathbf{x})) = \mathbb{I}(y f(\mathbf{x}) < 0)$ with $\mathcal{Y} = \{-1, +1\}$
Discontinuous, results in NP-hard optimization

Brier score (binary case)
 $L(y, \pi(\mathbf{x})) = (\pi(\mathbf{x}) - y)^2$ with $\mathcal{Y} = \{0, 1\}$
Least-squares on probabilities

Log-loss / Bernoulli loss / binomial loss (binary case)
For $\mathcal{Y} = \{0, 1\}$: $L(y, \pi(\mathbf{x})) = -y \log(\pi(\mathbf{x})) - (1 - y) \log(1 - \pi(\mathbf{x}))$
For $\mathcal{Y} = \{-1, +1\}$: $L(y, \pi(\mathbf{x})) = \log(1 + (\frac{\pi(\mathbf{x})}{1 - \pi(\mathbf{x})})^{-y})$
Assuming a logit-link $\pi(\mathbf{x}) = \exp(f(\mathbf{x})) / (1 + \exp(f(\mathbf{x})))$:
For $\mathcal{Y} = \{0, 1\}$: $L(y, f(\mathbf{x})) = -y \cdot f(\mathbf{x}) + \log(1 + \exp(f(\mathbf{x})))$
For $\mathcal{Y} = \{-1, +1\}$: $L(y, f(\mathbf{x})) = \log(1 + \exp(-y \cdot f(\mathbf{x})))$
Penalizes confidently-wrong predictions heavily

Brier score (multi-class case)
 $L(y, \pi(\mathbf{x})) = \sum_{k=1}^g (\pi_k(\mathbf{x}) - o_k(y))^2$

Log-loss (multi-class case)
 $L(y, \pi(\mathbf{x})) = - \sum_{k=1}^g o_k(y) \log(\pi_k(\mathbf{x}))$

Learning = Hypothesis space + Risk + Optimization
 $= \mathcal{H} + \mathcal{R}_{\text{emp}}(\boldsymbol{\theta}) + \arg \min_{\boldsymbol{\theta} \in \Theta} \mathcal{R}_{\text{emp}}(\boldsymbol{\theta})$

Components of Learning