

## Model Error

**Empirical Risk**  $\hat{R}_D(f) = \frac{1}{n} \sum \ell(y, f(x))$

**Population Risk**  $R(f) = \mathbb{E}_{x,y \sim p}[\ell(y, f(x))]$

It holds that  $\mathbb{E}_D[\hat{R}_D(\hat{f})] \leq R(\hat{f})$ . We call  $R(\hat{f})$  the generalization error.

**Bias Variance Tradeoff:**

Pred. error = **Bias**<sup>2</sup> + **Variance** + **Noise**  
 $\mathbb{E}_D[R(\hat{f})] = \mathbb{E}_x[(f^*(x) - \mathbb{E}_D[\hat{f}(x)])^2] + \mathbb{E}_x[(\hat{f}(x) - \mathbb{E}_D[\hat{f}(x)])^2] + \sigma$

**Bias:** how close  $\hat{f}$  can get to  $f^*$

**Variance:** how much  $\hat{f}$  changes with  $D$

## Regression

**Squared loss** (convex)

$$\frac{1}{n} \sum (y_i - f(x_i))^2 = \frac{1}{n} \|y - Xw\|_2^2$$
$$\nabla_w L(w) = 2X^T(Xw - y)$$

Solution:  $\hat{w} = (X^T X)^{-1} X^T y$

## Regularization

**Lasso Regression** (sparse)

$$\operatorname{argmin}_{w \in \mathbb{R}^d} \|y - \Phi w\|_2^2 + \lambda \|w\|_1$$

**Ridge Regression**

$$\operatorname{argmin}_{w \in \mathbb{R}^d} \|y - \Phi w\|_2^2 + \lambda \|w\|_2^2$$

$$\nabla_w L(w) = 2X^T(Xw - y) + 2\lambda w$$

Solution:  $\hat{w} = (X^T X + \lambda I)^{-1} X^T y$

## Cross-Validation

- For all folds  $i = 1, \dots, k$ :
  - Train  $\hat{f}_i$  on  $D' - D'_i$
  - Val. error  $R_i = \frac{1}{|D'_i|} \sum \ell(\hat{f}_i(x), y)$
- Compute CV error  $\frac{1}{k} \sum_{i=1}^k R_i$
- Pick model with lowest CV error

## Gradient Descent

Converges only for convex case.

$$w^{t+1} = w^t - \eta_t \cdot \nabla \ell(w^t)$$

For linear regression:

$$\|w^t - w^*\|_2 \leq \|I - \eta X^T X\|_{op}^t \|w^0 - w^*\|_2$$

$\rho = \|I - \eta X^T X\|_{op}^t$  con. speed for const.  $\eta$ .

Opt. fixed  $\eta = \frac{2}{\lambda_{\min} + \lambda_{\max}}$  and max.  $\eta \leq \frac{2}{\lambda_{\max}}$ .

**Momentum:**  $w^{t+1} = w^t + \gamma \Delta w^{t-1} - \eta_t \nabla \ell(w^t)$

## Classification

**Zero-One loss** not convex or continuous

$$\ell_{0-1}(\hat{f}(x), y) = \mathbb{I}_{y \neq \operatorname{sgn} \hat{f}(x)}$$

**Logistic loss**  $\log(1 + e^{y\hat{f}(x)})$

$$\nabla \ell(\hat{f}(x), y) = \frac{y_i x_i}{1 + e^{y_i \hat{f}(x)}}$$

**Hinge loss**  $\max(0, 1 - y\hat{f}(x))$

**Softmax Transformation**

$$\mathbb{P}[y = +1|x] = \frac{1}{1 + e^{-f(x)}}$$

**Multi-Class:**  $\hat{p}_k = \frac{e^{\hat{f}_k(x)}}{\sum_{i=1}^K e^{\hat{f}_i(x)}}$

## Linear Classifiers

$f(x) = w^T x$ , the decision boundary  $f(x) = 0$ .

**Maximum-Margin Solution:**

$$w_{MM} = \operatorname{argmax} \operatorname{margin}(w) \text{ with } \|w\|_2 = 1$$

Where  $\operatorname{margin}(w) = y_i w^T x_i$ .

**Support Vector Machines**

**Hard SVM**

$$\hat{w} = \min_w \|w\|_2 \text{ s.t. } \forall_i y_i w^T x_i \geq 1$$

**Soft SVM** allow "slack" in the constraints

$$\hat{w} = \min_{w, \xi} \frac{1}{2} \|w\|_2^2 + \lambda \sum_{i=1}^n \max(0, 1 - y_i w^T x_i)$$

## Metrics

Choose +1 as the more important class.

Prediction \ True Class	True Class	
	+1	-1
+1	TP	FP
-1	FN	TN

error<sub>1</sub>/FPR :  $\frac{FP}{TN + FP}$   
error<sub>2</sub>/FNR :  $\frac{FN}{TP + FN}$   
Precision :  $\frac{TP}{TP + FP}$   
TPR / Recall :  $\frac{TP}{TP + FN}$

**AUROC:** Plot TPR vs. FPR and compare different ROC's with area under the curve.

**F1-Score:**  $\frac{2TP}{2TP + FP + FN}$

## Kernels

Parameterize:  $w = \Phi^T \alpha$ ,  $K = \Phi \Phi^T$

A kernel is **valid** if  $K$  is sym.:  $k(x, z) = k(z, x)$

and psd:  $z^T K z \geq 0$

**lin.:**  $k(x, z) = x^T z$ , **poly.:**  $k(x, z) = (x^T z + 1)^m$

**rbf:**  $k(x, z) = \exp(-\frac{\|x - z\|_2^2}{\tau})$

$\alpha = 1 \Rightarrow$  laplacian kernel

$\alpha = 2 \Rightarrow$  gaussian kernel

**Kernel composition rules**

$k = k_1 + k_2$ ,  $k = k_1 \cdot k_2 \quad \forall c > 0. k = c \cdot k_1$ ,  
 $\forall f$  convex.  $k = f(k_1)$

**Mercers Theorem:** Valid kernels can be decomposed into a lin. comb. of inner products.

**Kern. Ridge Reg.**  $\frac{1}{n} \|y - K\alpha\|_2^2 + \lambda \alpha^T K \alpha$

## KNN Classification

- Pick  $k$  and distance metric  $d$
- For given  $x$ , find among  $x_1, \dots, x_n \in D$  the  $k$  closest to  $x \rightarrow x_{i_1}, \dots, x_{i_k}$
- Output the majority vote of labels

## Neural Networks

$w$  are the weights and  $\phi: \mathbb{R} \mapsto \mathbb{R}$  is a nonlinear

**activation function:**  $\phi(x, w) = \phi(w^T x)$

**ReLU:**  $\max(0, z)$ , **Tanh:**  $\frac{\exp(z) - \exp(-z)}{\exp(z) + \exp(-z)}$

**Sigmoid:**  $\frac{1}{1 + \exp(-z)}$

**Universal Approximation Theorem:** We can approximate any arbitrary smooth target function, with 1+ layer with sufficient width.

## Forward Propagation

Input:  $v^{(0)} = [x; 1]$  Output:  $f = W^{(L)} v^{(L-1)}$

Hidden:  $z^{(l)} = W^{(l)} v^{(l-1)}$ ,  $v^{(l)} = [\phi(z^{(l)}); 1]$

## Backpropagation

Non-convex optimization problem:

$$(\nabla_{w^{(L)}} \ell)^T = \frac{\partial \ell}{\partial w^{(L)}} = \frac{\partial \ell}{\partial f} \frac{\partial f}{\partial w^{(L)}}$$
$$(\nabla_{w^{(L-1)}} \ell)^T = \frac{\partial \ell}{\partial w^{(L-1)}} = \frac{\partial \ell}{\partial f} \frac{\partial f}{\partial z^{(L-1)}} \frac{\partial z^{(L-1)}}{\partial w^{(L-1)}}$$
$$(\nabla_{w^{(L-2)}} \ell)^T = \frac{\partial \ell}{\partial w^{(L-2)}} = \frac{\partial \ell}{\partial f} \frac{\partial f}{\partial z^{(L-1)}} \frac{\partial z^{(L-1)}}{\partial z^{(L-2)}} \frac{\partial z^{(L-2)}}{\partial w^{(L-2)}}$$

Only compute **the gradient**. Rand. init. weights by distr. assumption for  $\phi$ . ( $2/n_{in}$  for ReLu and  $1/n_{in}$  or  $1/(n_{in} + n_{out})$  for Tanh)

## Overfitting

**Regularization; Early Stopping; Dropout:** ignore hidden units with prob.  $p$ , after training use all units and scale weights by  $p$ ;  
**Batch Normalization:** normalize the input data (mean 0, variance 1) in each layer

**CNN**  $\phi(W * v^{(l)})$

The output dimension when applying  $m$  different  $f \times f$  filters to an  $n \times n$  image with padding  $p$  and stride  $s$  is:  $l = \frac{n+2p-f}{s} + 1$

## Unsupervised Learning

### k-Means Clustering

Optimization Goal (non-convex):

$$\hat{R}(\mu) = \sum_{i=1}^n \min_{j \in \{1, \dots, k\}} \|x_i - \mu_j\|_2^2$$

Lloyd's heuristics: Init. cluster centers  $\mu^{(0)}$ :

- Assign points to closest center
  - Update  $\mu_i$  as mean of assigned points
- Initialize with **k-Means++**:
- Random data point  $\mu_1 = x_i$
  - Add  $\mu_2, \dots, \mu_k$  rand., with prob: given  $\mu_{1:j}$  pick  $\mu_{j+1} = x_i$  where  $p(i) = \frac{1}{z} \min_{l \in \{1, \dots, j\}} \|x_i - \mu_l\|_2^2$

Find  $k$  by negligible loss decrease or reg.

## Principal Component Analysis

The optimal solution is given by  $z_i = w^T x_i$ . Optimization goal:

$$\hat{w} = \operatorname{argmin}_{\|w\|_2=1} \sum_{i=1}^n (w^T x_i)^2 = \operatorname{argmin}_{\|w\|_2=1} w^T \Sigma w$$

Where  $\Sigma = \frac{1}{n} \sum_{i=1}^n x_i x_i^T$  is the empirical covariance. Closed form solution given by the principal eigenvector of  $\Sigma$ , i.e.  $w = v_1$  for  $\lambda_1 \geq \dots \geq \lambda_d \geq 0$ :  $\Sigma = \sum_{i=1}^d \lambda_i v_i v_i^T$ . For  $k > 1$  we have to change the normalization to  $W^T W = I$  then we just take the first  $k$  principal eigenvectors so that  $W = [v_1, \dots, v_k]$ .

## PCA through SVD

The first  $k$  columns of  $V$  where  $X = U S V^T$ .

## Kernel PCA

$\Sigma = \frac{1}{n} \sum_{i=1}^n x_i x_i^T = X^T X \Rightarrow$  kernel trick:

$$\hat{\alpha} = \operatorname{argmax}_{\alpha} \frac{\alpha^T K^T K \alpha}{\alpha^T K \alpha}$$

Closed form solution:

$$\alpha^{(i)} = \frac{1}{\sqrt{\lambda_i}} v_i \quad K = \sum_{i=1}^n \lambda_i v_i v_i^T$$

A point  $x$  is projected as:  $z_i = \sum_{j=1}^n \alpha_j^{(i)} k(x_j, x)$

## Autoencoders

We want to minimize  $\frac{1}{n} \sum_{i=1}^n \|x_i - \hat{x}_i\|_2^2$ .

$$\hat{x} = f_{dec}(f_{enc}(x, \theta_{enc}); \theta_{dec})$$

Lin. activation func. & square loss  $\Rightarrow$  PCA

## Statistical Perspective

Assume that data is generated iid. by some  $p(x, y)$ . We want to find  $f: X \mapsto Y$  that minimizes the **population risk**.

**Opt. Predictor for the Squared Loss**

$f$  minimizing the population risk:

$$f^*(x) = \mathbb{E}[y | X = x] = \int y \cdot p(y | x) dy$$

Estimate  $\hat{p}(y | x)$  with MLE:

$$\theta^* = \operatorname{argmax}_{\theta} \hat{p}(y_1, \dots, y_n | x_1, \dots, x_n, \theta)$$
$$= \operatorname{argmin}_{\theta} - \sum_{i=1}^n \log p(y_i | x, \theta)$$

The MLE for linear regression is unbiased and has minimum variance among all unbiased estimators. However, it can overfit.

## Ex. Conditional Linear Gaussian

Assume Gaussian noise  $y = f(x) + \epsilon$  with  $\epsilon \sim \mathcal{N}(0, \sigma^2)$  and  $f(x) = w^T x$ :

$$\hat{p}(y | x, \theta) = \mathcal{N}(y; w^T x, \sigma^2)$$

The optimal  $\hat{w}$  can be found using MLE:

$$\hat{w} = \operatorname{argmax}_w p(y | x, \theta) = \operatorname{argmin}_w \sum_{i=1}^n (y_i - w^T x_i)^2$$

## Maximum a Posteriori Estimate

Introduce bias to reduce variance. The small weight assumption is a Gaussian prior  $w_i \sim \mathcal{N}(0, \beta^2)$ . The posterior distribution of  $w$  is

given by:  $p(w | x, y) = \frac{p(w) \cdot p(y | w, x)}{p(y | x)}$

Now we want to find the MAP for  $w$ :

$$\hat{w} = \underset{w}{\operatorname{argmax}} p(w | \bar{x}, \bar{y})$$

$$= \underset{w}{\operatorname{argmin}} \frac{\sigma^2}{\beta^2} \|w\|_2^2 + \sum_{i=1}^n (y_i - w^\top x_i)^2$$

Regularization can be understood as MAP inference, with different priors (= regularizers) and likelihoods (= loss functions).

## Statistical Models for Classification

$f$  minimizing the population risk:

$$f^*(x) = \underset{\hat{y}}{\operatorname{argmax}} p(\hat{y} | x)$$

This is called the Bayes' optimal predictor for the 0-1 loss. Assuming iid. Bernoulli noise, the conditional probability is:

$$p(y | x, w) \sim \operatorname{Ber}(y; \sigma(w^\top x))$$

Where  $\sigma(z) = \frac{1}{1 + \exp(-z)}$  is the sigmoid function. Using MLE we get:

$$\hat{w} = \underset{w}{\operatorname{argmin}} \sum_{i=1}^n \log(1 + \exp(-y_i w^\top x_i))$$

Which is the logistic loss. Instead of MLE we can estimate MAP, e.g. with a Gaussian prior:

$$\hat{w} = \underset{w}{\operatorname{argmin}} \lambda \|w\|_2^2 + \sum_{i=1}^n \log(1 + e^{-y_i w^\top x_i})$$

## Bayesian Decision Theory

Given  $p(y | x)$ , a set of actions  $A$  and a cost  $C : Y \times A \mapsto \mathbb{R}$ , pick the action with the maximum expected utility.

$$a^* = \underset{a \in A}{\operatorname{argmin}} \mathbb{E}_y[C(y, a) | x]$$

Can be used for asymmetric costs or abstention.

## Generative Modeling

Aim to estimate  $p(x, y)$  for complex situations using Bayes' rule.

## Naive Bayes Model

GM for classification tasks. Assuming for a class label, each feature is independent. This helps estimating  $p(x | y) = \prod_{i=1}^d p(x_i | y_i)$ .

## Gaussian Naive Bayes Classifier

Naive Bayes Model with Gaussians features. Estimate the parameters via MLE:

MLE for class prior:  $p(y) = \hat{p}_y = \frac{\operatorname{Count}(Y=y)}{n}$

MLE for feature distribution:

Where:  $p(x_i | y) = \mathcal{N}(x_i; \hat{\mu}_{y,i}, \sigma_{y,i}^2)$

$$\hat{\mu}_{y,i} = \frac{1}{\operatorname{Count}(Y=y)} \sum_{j | y_j=y} x_{j,i}$$

$$\hat{\sigma}_{y,i}^2 = \frac{1}{\operatorname{Count}(Y=y)} \sum_{j | y_j=y} (x_{j,i} - \hat{\mu}_{y,i})^2$$

Predictions are made by:

$$y = \underset{\hat{y}}{\operatorname{argmax}} p(\hat{y} | x) = \underset{\hat{y}}{\operatorname{argmax}} p(\hat{y}) \cdot \prod_{i=1}^d p(x_i | \hat{y})$$

Equivalent to decision rule for bin. class.:

$$y = \operatorname{sgn} \left( \log \frac{p(Y=+1 | x)}{p(Y=-1 | x)} \right)$$

Where  $f(x)$  is called the discriminant function. If the conditional independence assumption is violated, the classifier can be overconfident.

## Gaussian Bayes Classifier

No independence assumption, model the features with a multivariate Gaussian  $\mathcal{N}(x; \mu_y, \Sigma_y)$ :

$$\mu_y = \frac{1}{\operatorname{Count}(Y=y)} \sum_{j | y_j=y} x_j$$

$$\Sigma_y = \frac{1}{\operatorname{Count}(Y=y)} \sum_{j | y_j=y} (x_j - \hat{\mu}_y)(x_j - \hat{\mu}_y)^\top$$

This is also called the **quadratic discriminant analysis (QDA)**.

Linear Discriminant Analysis:  $\Sigma_+ = \Sigma_-$

Fisher LDA:  $p(y) = \frac{1}{2}$

Outlier detection with:  $p(x) \leq \tau$ .

## Avoiding Overfitting

MLE is prone to overfitting. Avoid this by restricting model class (fewer parameters, e.g. GNB) or using priors (restrict param. values).

## Generative vs. Discriminative

**Discriminative models:**

$p(y|x)$ , can't detect outliers, more robust

**Generative models:**

$p(x, y)$ , can be more powerful (detect outliers, missing values) if assumptions are met, are typically less robust against outliers

## Gaussian Mixture Model

Assume that data is generated from a convex combination of Gaussian distributions:

$$p(x|\theta) = p(x|\mu, \Sigma, w) = \sum_{j=1}^k w_j \mathcal{N}(x; \mu_j, \Sigma_j)$$

We don't have labels and want to cluster this data. The problem is to estimate the param. for the Gaussian distributions.

$$\underset{w, \mu, \Sigma}{\operatorname{argmin}} - \sum_{i=1}^n \log \sum_{j=1}^k w_j \cdot \mathcal{N}(x_i | \mu_j, \Sigma_j)$$

This is a non-convex objective. Similar to training a GBC without labels. Start with guess for our parameters, predict the unknown labels and then impute the missing data. Now we can get a closed form update.

## Hard-EM Algorithm

**E-Step:** predict the most likely class for each data point:

$$z_i^{(t)} = \underset{z}{\operatorname{argmax}} p(z | x_i, \theta^{(t-1)})$$

$$= \underset{z}{\operatorname{argmax}} p(z | \theta^{(t-1)}) \cdot p(x_i | z, \theta^{(t-1)})$$

**M-Step:** compute MLE of  $\theta^{(t)}$  as for GBC.

Problems: labels if the model is uncertain, tries to extract too much inf. Works poorly if clusters are overlapping. With uniform weights and spherical covariances is equivalent to k-Means with Lloyd's heuristics.

## Soft-EM Algorithm

**E-Step:** calculate the cluster membership weights for each point:

$$\gamma_j^{(t)}(x_i) = \frac{w_j \cdot p(x_i; \theta_j^{(t-1)})}{\sum_k w_k \cdot p(x_i; \theta_k^{(t-1)})}$$

**M-Step:** compute MLE with closed form:

$$w_j^{(t)} = \frac{1}{n} \sum_{i=1}^n \gamma_j^{(t)}(x_i) \quad \mu_j^{(t)} = \frac{\sum_{i=1}^n x_i \cdot \gamma_j^{(t)}(x_i)}{\sum_{i=1}^n \gamma_j^{(t)}(x_i)}$$

$$\Sigma_j^{(t)} = \frac{\sum_{i=1}^n \gamma_j^{(t)}(x_i)(x_i - \mu_j^{(t)})(x_i - \mu_j^{(t)})^\top}{\sum_{i=1}^n \gamma_j^{(t)}(x_i)}$$

Init. the weights as uniformly distributed, rand. or with k-Means++ and for variances use spherical init. or empirical covariance of the data. Select  $k$  using cross-validation.

## Degeneracy of GMMs

GMMs can overfit with limited data. Avoid this by add  $v^2 I$  to variance, so it does not collapse (equiv. to a Wishart prior on the covariance matrix). Choose  $v$  by cross-validation.

## Gaussian-Mixture Bayes Classifiers

Assume that  $p(x | y)$  for each class can be modelled by a GMM.

$$p(x | y) = \sum_{j=1}^{k_y} w_j^{(y)} \mathcal{N}(x; \mu_j^{(y)}, \Sigma_j^{(y)})$$

Giving highly complex decision boundaries:

$$p(y | x) = \frac{1}{z} p(y) \sum_{j=1}^{k_y} w_j^{(y)} \mathcal{N}(x; \mu_j^{(y)}, \Sigma_j^{(y)})$$

## GMMs for Density Estimation

Can be used for anomaly detection or data imputation. Detect outliers, by comparing the estimated density against  $\tau$ . Allows to control the FP rate. Use ROC curve as evaluation criterion and optimize using CV to find  $\tau$ .

## General EM Algorithm

**E-Step:** Take the expected value over latent variables to generate a likelihood function  $Q$ :

$$Q(\theta; \theta^{(t-1)}) = \mathbb{E}_Z[\log p(X, Z | \theta) | X, \theta^{(t-1)}]$$

$$= \sum_{i=1}^n \sum_{z_i=1}^k \gamma_{z_i}(x_i) \log p(x_i, z_i | \theta)$$

with  $\gamma_z(x) = p(z | x, \theta^{(t-1)})$

**M-Step:** Compute MLE / Maximize:

$$\theta^{(t)} = \underset{\theta}{\operatorname{argmax}} Q(\theta; \theta^{(t-1)})$$

We have monotonic convergence, each EM-iteration increases the data likelihood.

## GANs

Learn  $f$ : "simple" distr.  $\mapsto$  non linear distr. Computing likelihood of the data becomes hard, therefore we need a different loss.

$$\min_{w_G} \max_{w_D} \mathbb{E}_{x \sim p_{\text{data}}} [\log D(x, w_D)]$$

$$+ \mathbb{E}_{z \sim p_z} [\log(1 - D(G(z, w_G), w_D))]$$

Training requires finding a saddle point. For a fixed  $G$ , the optimal discriminator is:

$$D_G(x) = \frac{p_{\text{data}}(x)}{p_{\text{data}}(x) + p_G(x)}$$

Powerful discriminator could lead to memorization of finite data. Other issues are oscillations/divergence or mode collapse.

One possible performance metric:

$$DG = \max_{w_D} M(w_G, w'_D) - \min_{w'_G} M(w'_G, w_D)$$

Where  $M(w_G, w_D)$  is the training objective.

## Various

### Derivatives:

$$\nabla_x x^\top A = A \quad \nabla_x a^\top x = \nabla_x x^\top a = a$$

$$\nabla_x b^\top A x = A^\top b \quad \nabla_x x^\top x = 2x \quad \nabla_x x^\top A x = 2A x$$

$$\nabla_w \|y - Xw\|_2^2 = 2X^\top (Xw - y)$$

### Bayes Theorem:

$$p(y | x) = \frac{1}{p(x)} \underbrace{p(y) \cdot p(x | y)}$$

### Normal Distribution:

$$f(x) = \frac{1}{\sigma\sqrt{2}} \exp\left(-\frac{(x-\mu)^2}{\sigma^2}\right)$$