

Statistical Classifiers

Bayesian Classifier

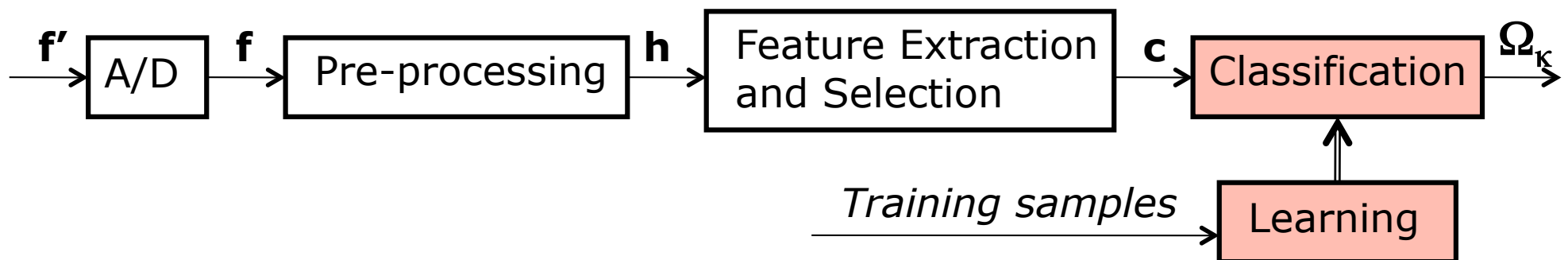


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Pattern Recognition Pipeline



■ Feature Extraction and Selection

- Heuristic feature extraction methods
- Analytic feature extraction methods
- Objective function for “goodness” of feature vector
- Search method for exploring the feature space

■ Classification

- The step where the actual “recognition” takes place.
- Assigns the transformed input signal to a class.
- Labelled data can be critical in the recognition success.

Decision Function



- Goal: Map the computed feature vector \vec{c} to a class

$$\Omega_{\kappa} \quad \vec{c} \xrightarrow{\delta(\Omega_{\kappa} | \vec{c})} \Omega_{\kappa}$$

- The decision function $\delta()$ can be a probabilistic decision function.

$$\sum_{\kappa=1}^K \delta(\Omega_{\kappa} | \vec{c}) = 1$$

- Given a feature vector \vec{c} , there is a certain probability that we will decide that the observed signal belongs to a particular class.
- A probabilistic decision function expresses the fact that there is uncertainty in our decision making process.

Decision Function - continued



- Other times, the decision function is a binary function of the form:

$$\delta(\Omega_k | \vec{c}) = \begin{cases} 1 & \text{for } \Omega_k, \text{ if it is decided that } \vec{c} \in \Omega_k \\ 0 & \text{for all other classes} \end{cases}$$

- In these cases the decision function can also be represented by a binary vector, with all zeroes, except the class to which the vector \vec{c} belongs to.

Common Assumptions



- Very often during classification we make the following assumptions:
 1. There exists a rejection class Ω_0 .
 2. Each classification decision has individual costs associated with it. It is the cost of making a mistake.
 3. After having classified a large number of samples, we are able to estimate the average costs/risk.

Statistical Classifiers



- We have briefly seen classifiers that base their decision based on distances from a representative sample of each class (i.e. mean), or on decision boundaries.
- Statistical classifiers are based on the following idea:
 1. Compute the risk associated with the classification of a pattern.
 2. Compute the decision rule by minimizing the total risk.
- The final decision rule (that minimizes the risk) leads to the optimal classifier.

Statistics Review



■ Mean vector (expectation):

- Continuous: $E\{X\} = \int xp(x)dx$

- Discrete: $\mu_X = \frac{1}{N} \sum_{i=1}^N x_i$

■ Variance of scalar random variable

- Continuous: $Var\{X\} = E\left\{\left(X - E\{X\}\right)^2\right\}$

- Discrete: $\sigma_X^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \mu_X)^2$

■ Variance of vector data (a.k.a. covariance matrix, or variance-covariance matrix, or dispersion matrix)

$$Var\{\vec{X}\} = E\left\{\left(\vec{X} - E\{\vec{X}\}\right)\left(\vec{X} - E\{\vec{X}\}\right)^T\right\}$$

Parametric Densities



- Parametric density functions are densities that are completely defined by their parameters.
- For example, in a normal distribution, the pdf is completely described by the mean and the variance.
- In general, parametric density functions are of the

form:

$$\vec{c} \approx p(\vec{c}|\vec{\alpha})$$

where $\vec{\alpha}$ is a parameter vector that has to be estimated.

- Example: Normally distributed feature vectors

$$\vec{c} \approx \mathcal{N}(\vec{c}, \vec{\mu}, \Sigma)$$

where the parameters $\vec{\mu}, \Sigma$ can be estimated via maximum likelihood estimation.

Classification Risk – a first look



- Recall that statistical classifiers are based on the following 2-step process:
 1. Compute the risk associated with the classification of a pattern.
 2. Compute the decision rule by minimizing the total risk.
- We need a way of quantifying the risk associated with a classifier.
- For that we need to first establish a cost for each classification decision.

Cost Function



- Let $r_{\lambda,K} \in R$ denote the **cost** for classifying a pattern as belonging to class Ω_λ when it truly belongs to class Ω_K .
- The **individual decision cost** $r_{\lambda,K}$ has to be defined by the user of the classifier.
- A cost function (usually) should fulfill the following inequality:

$$0 \leq r_{K,K} \leq r_{\lambda,K}$$

where $r_{K,K}$ is the correct decision.

- In the presence of a rejection class Ω_0 :

$$r_{K,K} \leq r_{0,K} \leq r_{\lambda,K}$$

Computing the Optimal Decision Rule



- In order to compute the optimal decision rule we need to perform the following steps:

1. Compute the probability of misclassification

$$p(\Omega_\lambda | \Omega_\kappa)$$

2. Compute the **risk** $R(\delta)$ associated with using a **particular decision function** $\delta()$, including correct decisions, as well as misclassifications:

$$R(\delta) = \sum_{\forall \kappa, \lambda} p(\Omega_\kappa) p(\Omega_\lambda | \Omega_\kappa) r_{\lambda, \kappa}$$

3. Minimize the risk over all different decision rules

$$\hat{\delta} = \arg \min_{\delta} R(\delta)$$

Computing the Prob. of Misclassification



- We want to compute the probability of misclassifying a signal as belonging to class Ω_λ when it truly belongs to class Ω_κ , $p(\Omega_\lambda|\Omega_\kappa)$

- By the definition of conditional probabilities:

$$p(A|B) = p(A,B)/p(B)$$

- Given two jointly distributed random variables A and B, the marginal distribution of A is simply the probability distribution of A ignoring information about B. It is typically calculated by integrating the joint probability distribution over B:

$$\text{Marginal } p(A) = \int_B p(A,b) pb$$

Computing the Prob. of Misclassification (2)



- Given these facts, one can derive the probability of misclassification by starting with the conditional probability and doing a marginalization over \vec{c} .

$$\begin{aligned}
 p(\Omega_\lambda, \vec{c} | \Omega_\kappa) &= \frac{p(\Omega_\lambda, \vec{c}, \Omega_\kappa)}{p(\Omega_\kappa)} \\
 &= \frac{p(\Omega_\lambda, \vec{c}, \Omega_\kappa)}{p(\Omega_\kappa)} \frac{p(\vec{c}, \Omega_\kappa)}{p(\vec{c}, \Omega_\kappa)} \\
 &= \frac{p(\Omega_\lambda, \vec{c}, \Omega_\kappa)}{p(\vec{c}, \Omega_\kappa)} \frac{p(\vec{c}, \Omega_\kappa)}{p(\Omega_\kappa)} \\
 &= p(\Omega_\lambda | \vec{c}, \Omega_\kappa) p(\vec{c} | \Omega_\kappa)
 \end{aligned}$$

Computing the Prob. of Misclassification (3)



- We have shown that $p(\Omega_\lambda, \vec{c} | \Omega_\kappa) = p(\Omega_\lambda | \vec{c}, \Omega_\kappa) p(\vec{c} | \Omega_\kappa)$
- However what we observe is just the feature vector \vec{c} and not both \vec{c} and Ω_κ .
- So we replace this term with a probabilistic decision for class Ω_λ , given that we have observed \vec{c} :

$$p(\Omega_\lambda, \vec{c} | \Omega_\kappa) = \delta(\Omega_\lambda | \vec{c}) p(\vec{c} | \Omega_\kappa)$$

- We can now do a marginalization over \vec{c} :

$$p(\Omega_\lambda | \Omega_\kappa) = \int_{R_{\vec{c}}} \delta(\Omega_\lambda | \vec{c}) p(\vec{c} | \Omega_\kappa) d\vec{c}$$

Computing the Optimal Decision Rule - revisit



- In order to compute the optimal decision rule we need to perform the following steps:

1. Compute the probability of misclassification

$$p(\Omega_\lambda | \Omega_\kappa) = \int \delta(\Omega_\lambda | \vec{c}) p(\vec{c} | \Omega_\kappa) d\vec{c}$$

2. Compute the **risk** $R(\delta)$ associated with using a **particular decision function** $\delta()$, including correct decisions, as well as misclassifications:

$$R(\delta) = \sum_{\forall \kappa, \lambda} p(\Omega_\kappa) p(\Omega_\lambda | \Omega_\kappa) r_{\lambda, \kappa}$$

3. Minimize the risk over all different decision rules

$$\hat{\delta} = \arg \min_{\delta} R(\delta)$$

Computing the Risk of a Decision Function



- The risk $R(\delta)$ associated with using a particular decision function $\delta(\cdot)$ for a specific class Ω_k is:

$$\begin{aligned}
 R(\delta|\Omega_k) &= \sum_{\lambda=0}^K p(\Omega_\lambda|\Omega_k) r_{\lambda,K} \\
 &= \sum_{\lambda=0}^K \int_{R_{\vec{c}}} \delta(\Omega_\lambda|\vec{c}) p(\vec{c}|\Omega_k) d\vec{c} r_{\lambda,K}
 \end{aligned}$$

- For the overall risk, we have to sum over all the classes, taking under consideration the probability of occurrence of each class.

$$R(\delta) = \sum_{k=1}^K R(\delta|\Omega_k) p(\Omega_k) = \int_{R_{\vec{c}}} \sum_{\lambda=0}^K \sum_{k=1}^K r_{\lambda,K} p(\Omega_k) p(\vec{c}|\Omega_k) \delta(\Omega_\lambda|\vec{c}) d\vec{c}$$

$u_\lambda(\vec{c})$ ← measurement value

Objective Function



- The overall risk $R(\delta)$ can then be written more compactly as:

$$R(\delta) = \int_{R_{\vec{c}}} \sum_{\lambda=0}^K u_{\lambda}(\vec{c}) \delta(\Omega_{\lambda} | \vec{c}) d\vec{c}$$

- Goal: Derive an optimal decision rule which minimizes overall risk:

$$\hat{\delta} = \arg \min_{\delta} R(\delta) = \arg \min_{\delta} \int_{R_{\vec{c}}} \sum_{\lambda=0}^K u_{\lambda}(\vec{c}) \delta(\Omega_{\lambda} | \vec{c}) d\vec{c}$$

- Conclusion: The optimal classifier will decide for the class that leads to the smallest measurement value $u_{\lambda}(\vec{c})$.

Optimal Decision Rule



- Let $u_{min}(\vec{c})$ be the smallest possible measurement value among all possible classes.

$$u_{min}(\vec{c}) = \min_{\lambda} u_{\lambda}(\vec{c})$$

- Then, the optimal decision rule is:

$$\delta(\Omega_{\lambda}|\vec{c}) = \begin{cases} 1 & \text{if } u_{\lambda}(\vec{c}) = u_{min}(\vec{c}) \\ 0 & \text{otherwise} \end{cases}$$



A Remark on the Measurement Value

- The computation of $u_\lambda(\vec{c})$ can be done by a vector product calculation:

$$u_\lambda(\vec{c}) = \sum_{\kappa=1}^K r_{\lambda,\kappa} p(\Omega_\kappa) p(\vec{c}|\Omega_\kappa)$$

$$= [r_{\lambda,1}, r_{\lambda,2}, \dots, r_{\lambda,K}] \begin{bmatrix} p(\Omega_1) p(\vec{c}|\Omega_1) \\ p(\Omega_2) p(\vec{c}|\Omega_2) \\ \vdots \\ p(\Omega_K) p(\vec{c}|\Omega_K) \end{bmatrix}$$

independent of \vec{c}

Cost Functions



- So far we have considered the user-defined cost function $r_{\lambda,\kappa}$, where $\lambda = 0, 1, 2, \dots, K$ and $\kappa = 1, 2, \dots, K$ and where K is the number of classes. So the user must specify $(K+1)K$ different cost values.

- A simpler cost setup involves just 3 distinct cost functions:

$$r_{\kappa,\kappa} = r_c \quad \forall \kappa \quad (\text{correct classification})$$

$$r_{0,\kappa} = r_r \quad \forall \kappa \quad (\text{reject})$$

$$r_{\lambda,\kappa} = r_f \quad \forall \kappa \neq \lambda \quad (\text{false classification})$$

- So one can also think of the total cost of a decision function as:

$$R(\delta) = p_c r_c + p_f r_f + p_r r_r$$

(0,1)-Cost Function



- A special case of cost function is the (0,1)-cost function which:
 - uses no rejection class
 - has an $r_{\kappa,\kappa} = r_c = 0 \quad \forall \kappa$ correct decision cost
 - has an $r_{\lambda,\kappa} = r_f = 1 \quad \forall \kappa \neq \lambda$ false decision cost
- The risk function for the (0,1) cost function is a simplified version of the general $R(\delta)$:

$$R(\delta) = p_c r_c + p_f r_f + p_r r_r = p_f$$

- Thus, a classifier that minimizes the risk for a (0,1)-cost function is equivalent to the classifier that minimizes the error probability.

Decision rule of a (0,1)-Cost Function



- Using a (0,1)-cost function simplifies the measurement value:

$$u_{\lambda}(\vec{c}) = \sum_{\kappa=1}^K r_{\lambda,\kappa} p(\Omega_{\kappa}) p(\vec{c}|\Omega_{\kappa}) = \sum_{\substack{\kappa=1 \\ \kappa \neq \lambda}}^K p(\Omega_{\kappa}) p(\vec{c}|\Omega_{\kappa})$$

- Recall that the optimal decision rule is:

$$\delta(\Omega_{\lambda}|\vec{c}) = \begin{cases} 1 & \text{if } u_{\lambda}(\vec{c}) = u_{\min}(\vec{c}) = \min_{\kappa} u_{\kappa}(\vec{c}) \\ 0 & \text{otherwise} \end{cases}$$

- Notice that $u_{\lambda}(\vec{c})$ is minimal when the largest summand is left out, i.e. when the class Ω_{κ} with the largest $p(\Omega_{\kappa}) p(\vec{c}|\Omega_{\kappa})$ product is not included in the summation.

Measurement Value of a (0,1)-Cost Function



- More specifically, minimizing $u_\lambda(\vec{c})$ for a (0,1)-cost function involves:

$$\begin{aligned} u_{min}(\vec{c}) &= \min_{\lambda} u_\lambda(\vec{c}) \\ &= \min_{\lambda} \sum_{\substack{\kappa=1 \\ \kappa \neq \lambda}}^K p(\Omega_\kappa) p(\vec{c} | \Omega_\kappa) \end{aligned}$$

- But the sum is minimal when the largest summand is left out. The largest term of the sum is realized for the class with the largest $p(\Omega_\kappa) p(\vec{c} | \Omega_\kappa)$ term.
- How can we exclude this from the sum?
- Assign \vec{c} to the class with the largest $p(\Omega_\kappa) p(\vec{c} | \Omega_\kappa)$ term. Then through the $\kappa \neq \lambda$ condition the term is excluded from the sum.

Measurement Value of a (0,1)-Cost Function



- The measurement value then becomes:

$$u_{\min}(\vec{c}) = \min_{\lambda} \sum_{\substack{\kappa=1 \\ \kappa \neq \lambda}}^K p(\Omega_{\kappa}) p(\vec{c} | \Omega_{\kappa})$$

Selecting the largest summand

$$= \max_{\lambda} p(\Omega_{\lambda}) p(\vec{c} | \Omega_{\lambda})$$

Dividing with a term independent of the maximizing argument λ

$$= \max_{\lambda} \frac{p(\Omega_{\lambda}) p(\vec{c} | \Omega_{\lambda})}{p(\vec{c})}$$

Using the Bayesian rule

$$= \max_{\lambda} p(\Omega_{\lambda} | \vec{c})$$

a-posteriori probability

Optimal Decision Rule Revisited



- So, given a feature vector \vec{c} we compute for each class the a-posteriori probability and decide for the class with the largest probability.
- Lemma: The classifier that minimizes the probability for misclassification (minimizes p_f) applies the following decision rule:

$$\delta(\Omega_\lambda | \vec{c}) = \begin{cases} 1 & \text{if } \lambda = \arg \max_{\kappa} p(\Omega_\kappa | \vec{c}) \\ 0 & \text{otherwise} \end{cases}$$

Bayesian decision rule

Bayesian Decision Rule



- The Bayes decision rule is a very important result in pattern recognition.
- It states that if we want to have a classification scheme that minimizes the probability of misclassifications, then the only thing one needs to do is to:
 - a. Compute the posterior probabilities $p(\Omega_k | \vec{c})$
 - b. Decide for the class that give the maximum posterior probability.
- Simple concept:

Finding the optimal classifier requires finding the posterior probabilities.

Bayesian Classifier



- Definition: A classifier whose decision rule is based on the maximization of posterior probabilities is called a *Bayesian classifier*.
- So pattern recognition is then done/solved in term of classification.
- All we need to do is given some training data to compute the posterior probability $p(\Omega_k | \vec{c})$.
- A simple task. Or is it?

Bayesian Classifier



- Obtaining accurate estimates of the posterior probabilities from training data can be challenging.
- One of the topics of Pattern Recognition is to find good methodologies for approximating the posterior probabilities.
- So in theory, there is no other classifier that can achieve a lower error probability than a **(0,1)-Bayesian classifier**. Let us denote the error probability of a Bayesian classifier as p_B .
- In general, this error probability p_B will act as a lower bound when discussing the error probabilities of other classifiers.

Remarks



1. Many classifiers try to approximate the Bayesian classifier.

Caution: a $(0,1)$ -cost function must make sense, do not force a $(0,1)$ -cost function if it doesn't fit the application.

2. The Bayesian classifier requires complete knowledge about $p(\Omega_k | \vec{c})$.

How do we get enough training data?

Is the training data appropriate? In other words are our samples good examples of the real population?

Remarks - continued



3. Modeling of $p(\Omega_k | \vec{c})$ is a key issue.

For instance:

In speech recognition we don't classify based on a single feature but rather on a sequence of features.

How do we handle feature sequences in the posterior probability computation?

How do we deal with the fact that the image data we get is a projection from 3D to 2D, so we already have information loss?