

Non-parametric methods

Introduction to Machine Learning, Ch. 8, E.Alpaydin,

P. Faion, P. Byvshev

UOs

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Introduction

Nonparametric Estimation

- Parametric (single global model), semiparametric (small number of local models)
- Nonparametric (no model): Similar inputs have similar outputs
- Density function, discriminant change smoothly
- The data speak for itself
- For a given test X a 'closest' subset in training data is used for the prediction

In machine learning literature, nonparametric methods are also called instance-based or memory-based learning algorithms, since what they do is store the training instances in a lookup table and interpolate from these.

Nonparametric Density Estimation

Naive histogram estimator

The estimate is the sum of influences of x^t whose regions include x . Because this region of influence is hard (0 or 1), the estimate is not a continuous function and has jumps at $x \pm h/2$.

$$\hat{p}(x) = \frac{\#(x^t \text{ in the same bin as } x)}{Nh} \quad (1)$$

A smooth weight function called a kernel to make estimate smooth. The most popular is the Gaussian kernel:

$$\hat{p}(x) = \frac{1}{Nh} \sum_{t=1}^N K\left(\frac{x - x^t}{h}\right) \quad (2)$$

$$K(u) = \frac{1}{2\pi} \exp\left(\frac{-u^2}{2}\right) \quad (3)$$

k-Nearest Neighbor Estimator

The nearest neighbor class of estimators adapts the amount of smoothing to the local density of data. The degree of smoothing is controlled by k , the number of neighbors taken into account, which is much smaller than N , the sample size.

For each x : $d_1(x) \leq d_2(x) \leq \dots \leq d_N(x)$ is defined

The k -nearest neighbor (k -nn) density estimate is:

$$\hat{p}(x) = \frac{k}{2Nd_k(x)} \quad (4)$$

But there are still parameters!?

- output still depends on *smoothing parameters*: kernel spread h or number of neighbors k
 - small parameters lead to small bias, but large variance and vice versa
 - if the noise in the data is small, but we choose k or h high, we *oversmooth*
 - if the noise in the data is high, but we choose k or h small, we *undersmooth*
- ⇒ use cross-validation to find the best parameter

Multivariate kernel density estimator

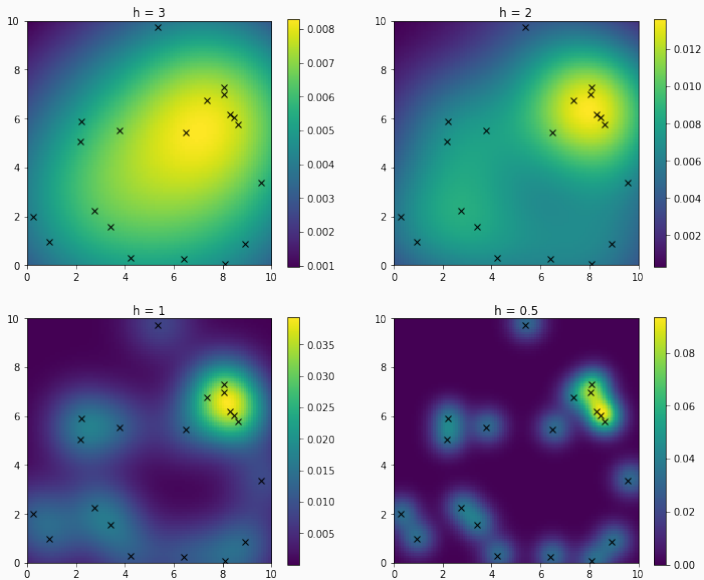
m-dimensional observations: $X = (x^t)_{t=1}^N$

Kernel density estimator:

$$\hat{p}(x) = \frac{1}{Nh^m} \sum_{t=1}^N K\left(\frac{x - x^t}{h}\right) \quad (5)$$

$$K(u) = \frac{1}{(2\pi)^{m/2} |S|^{1/2}} \exp\left(-\frac{1}{2} u^T S^{-1} u\right) \quad (6)$$

Multivariate kernel density estimator



Nonparametric Classification

Nonparametric Classification

We can estimate class-conditional densities $p(x|C_i)$ also with a nonparametric kernel approach:

$$\hat{p}(x|C_i) = \frac{1}{N_i h^d} \sum_{t=1}^N K\left(\frac{x - x^t}{h}\right) r_i^t \quad (7)$$

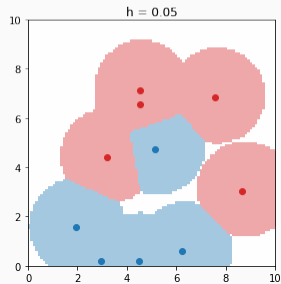
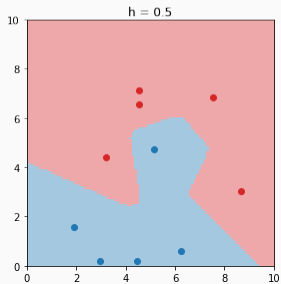
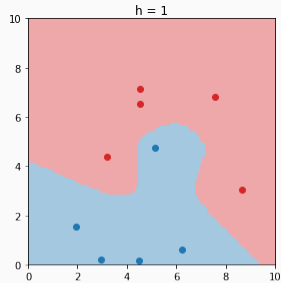
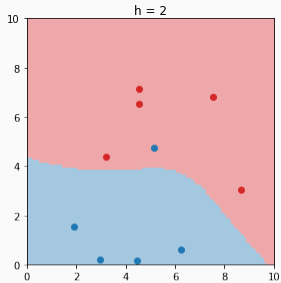
For the prior density of the classes, we have the MLE:

$$\hat{p}(C_i) = \frac{N_i}{N} \quad (8)$$

Then classify with:

$$\text{class}(x) = \underset{i}{\operatorname{argmax}} \{ \hat{p}(x|C_i) \hat{p}(C_i) \} \quad (9)$$

Nonparametric Classification



Nonparametric Classification

For the knn approach, we get the following densities:

$$\hat{p}(x|C_i) = \frac{k_i}{N_i V^k(x)} \quad (10)$$

$V^k(x)$: the volume of the d -dimensional hypersphere centered at x , with radius $\|x - x_{(k)}\|$ where $x_{(k)}$ is the k -th nearest observation to x (among all neighbors from all classes of x)

k_i : the number of neighbors from the k nearest neighbors, that belong to class C_i

Nonparametric Classification

We can now calculate the marginal probability for the data:

$$\hat{p}(x) = \sum_i \hat{p}(x|C_i) \hat{p}(C_i) \quad (11)$$

$$= \sum_i \frac{k_i}{N_i V^k(x)} \frac{N_i}{N} \quad (12)$$

$$= \sum_i \frac{k_i}{N V^k(x)} \quad (13)$$

$$= \frac{k}{N V^k(x)} \quad (14)$$

Classification is done with:

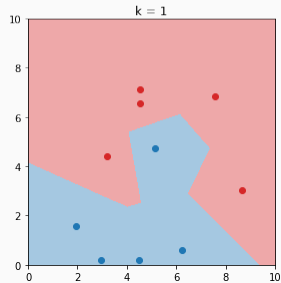
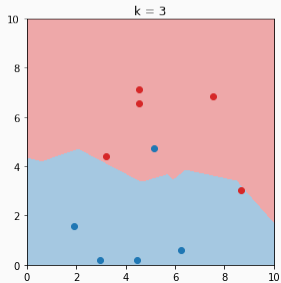
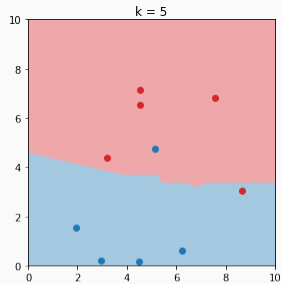
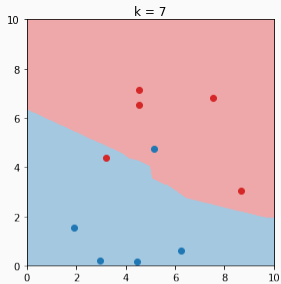
$$\hat{p}(C_i|x) = \frac{\hat{p}(x|C_i)\hat{p}(C_i)}{\hat{p}(x)} \quad (15)$$

$$= \frac{\frac{k_i}{N_i V^k(x)} \frac{N_i}{N}}{\frac{k}{N V^k(x)}} \quad (16)$$

$$= \frac{k_i}{k} \quad (17)$$

$$\text{class}(x) = \text{argmax}_i \{ \hat{p}(C_i|x) \} \quad (18)$$

Nonparametric Classification



Condensed Nearest Neighbor

In order to decrease time and space complexity, the training set can be condensed. The error should not change.

$$Z = \{\}$$

While Z still changes:

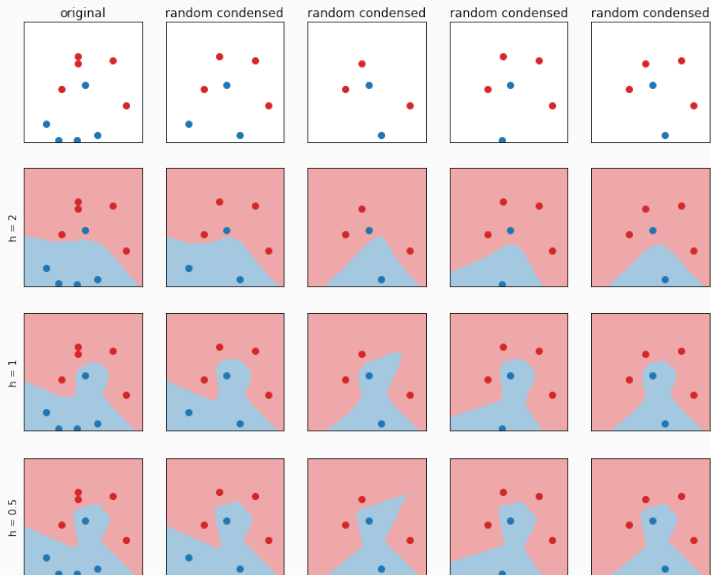
For all $x \in X$ (in random order):

Find $z \in Z$ which is closest to x

If $\text{class}(x) \neq \text{class}(z)$: add x to Z

The algorithm can yield quite different results, because of the randomness.

Condensed Nearest Neighbor



Nonparametric classification relies on a *distance measure* to specify, which class is the "closest".

Different distance measures make more or less sense, depending on the problem.

For parametric we had e.g. the Mahalanobis distance:

$$D(x, m_i) = (x - m_i)^T S_i^{-1} (x - m_i) \quad (19)$$

Distance-Based Classification

The main idea of nonparametric distance learning is to have a distance measure for each neighborhood, e.g. in k-nn.

Thus we need a distance measure between a point and an instance of the training set, e.g. with Mahalanobis

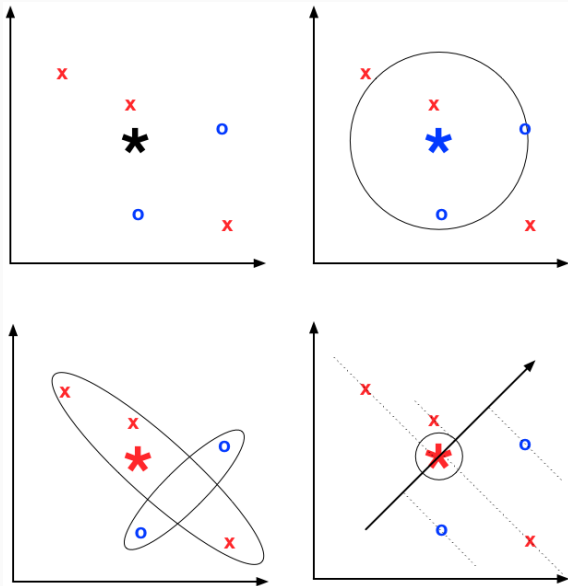
$$D(x, x^t | M) = (x - x^t)^T M (x - x^t) \quad (20)$$

where M is a parameter and can be learned from the training set to optimize this measure (e.g. with the *large margin nearest neighbor* algorithm).

$$D(x, x^t | M) = (x - x^t)^T M (x - x^t) \quad (21)$$

Overfitting high dimensional data can be reduced by using a low-rank approximation of M . The Mahalanobis distance for this sparse M corresponds to the (squared) euclidean distance in a subspace.

Distance-Based Classification



Hamming distance

Hamming distance between two strings of equal length is the number of positions at which the corresponding symbols are different.

$$HD(x, x^t) = \sum_{j=1}^d 1(x_j \neq x_j^t) \quad (22)$$

Local outlier factor that compares the denseness of the neighborhood of an instance with the average denseness of the neighborhoods of its neighbors

$$LOF(x) = \frac{d_k(x)}{\sum_{s \in N(x)} d_k(s) / |N(x)|} \quad (23)$$

If $LOF(x)$ is close to 1, x is not an outlier; as it gets larger, the probability that it is an outlier increases

Nonparametric Regression

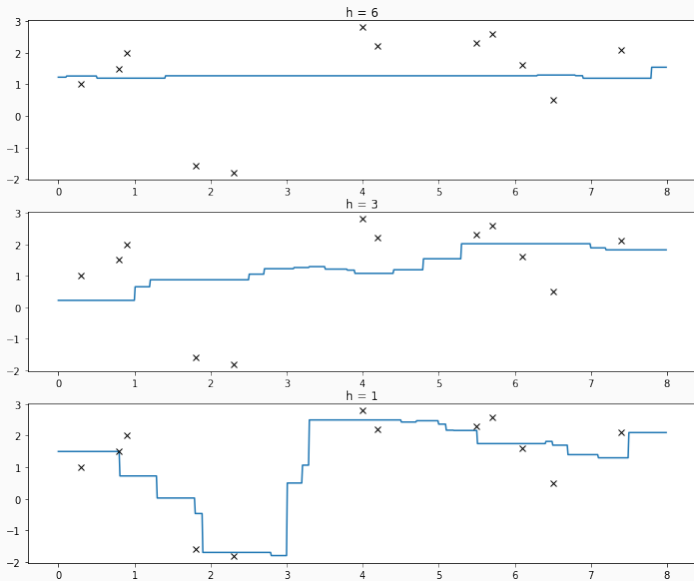
Running Mean Smoother

$$g(x) = \frac{\sum_{t=1}^N w\left(\frac{x-x^t}{h}\right) r^t}{\sum_{t=1}^N w\left(\frac{x-x^t}{h}\right)} \quad w(u) = \begin{cases} 1, & \text{if } |u| < h \\ 0, & \text{otherwise} \end{cases} \quad (24)$$

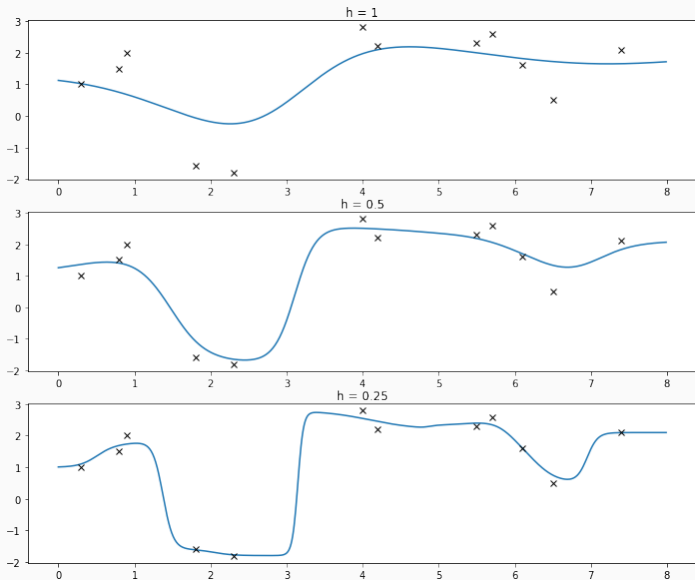
Kernel Smoother

$$g(x) = \frac{\sum_{t=1}^N K\left(\frac{x-x^t}{h}\right) r^t}{\sum_{t=1}^N K\left(\frac{x-x^t}{h}\right)} \quad (25)$$

Nonparametric Regression: Smoothing Models

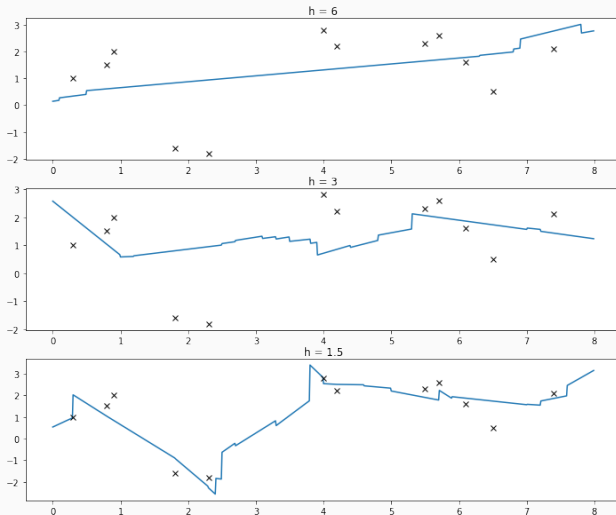


Nonparametric Regression: Smoothing Models



Nonparametric Regression: Smoothing Models

Running Line Smoother



Remarks

- algorithms were proposed many years ago but were only recently used due to computational complexity
- for high dimensional data, the amount of needed instances increases exponentially
- another famous example are support vectore machines (see later presentation)