

# Streaming Machine Learning Classification

**Alessio Bernardo**

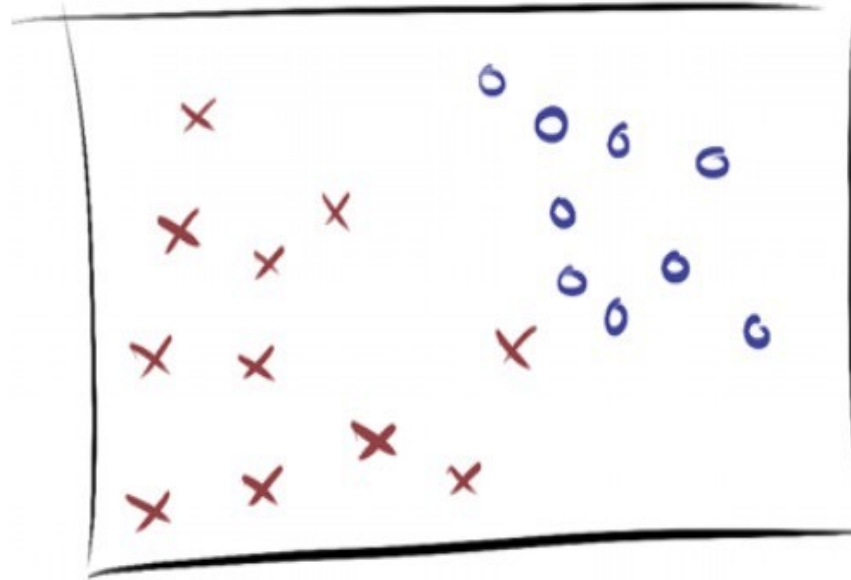
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# SML Classification models



# Naïve Bayes

- Based on Bayes Theorem, where  $c$  is the class and  $d$  is the instance to classify:

$$P(c|d) = \frac{P(c) * P(d|c)}{P(d)}$$

- Estimate the probability of observing attribute  $a$  and the prior probability  $P(c)$ :

$$P(c|d) = \frac{P(c) * \prod_{a \in d} P(a|c)}{P(d)}$$

John, G. H., & Langley, P. **Estimating continuous distributions in Bayesian classifiers**. arXiv preprint 2013.

# Naïve Bayes

## Mean and Variance with a batch of n samples

$$\hat{x} = \frac{1}{n} * \sum_{i=1}^n x_i \qquad \sigma^2 = \frac{1}{n-1} * \sum_{i=1}^n (x_i - \hat{x})^2$$

## Mean and Variance with a stream $x_1, \dots, x_i, \dots, x_n$

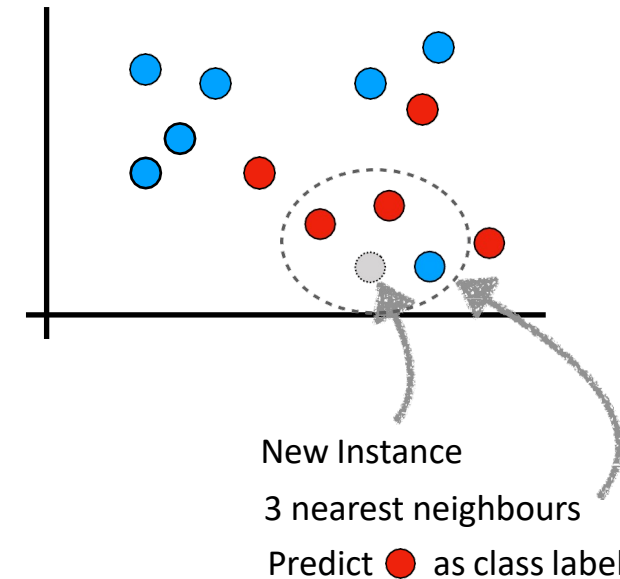
$$\begin{aligned} s_i &= s_{i-1} + x_i \\ \hat{x}_i &= \frac{s_i}{i} \end{aligned} \qquad \begin{aligned} q_i &= q_{i-1} + x_i^2 \\ \sigma_i^2 &= \frac{1}{i-1} * (q_i - \frac{s_i^2}{i}) \end{aligned}$$

John, G. H., & Langley, P. **Estimating continuous distributions in Bayesian classifiers.** arXiv preprint 2013.

# K-Nearest Neighbours (KNN)

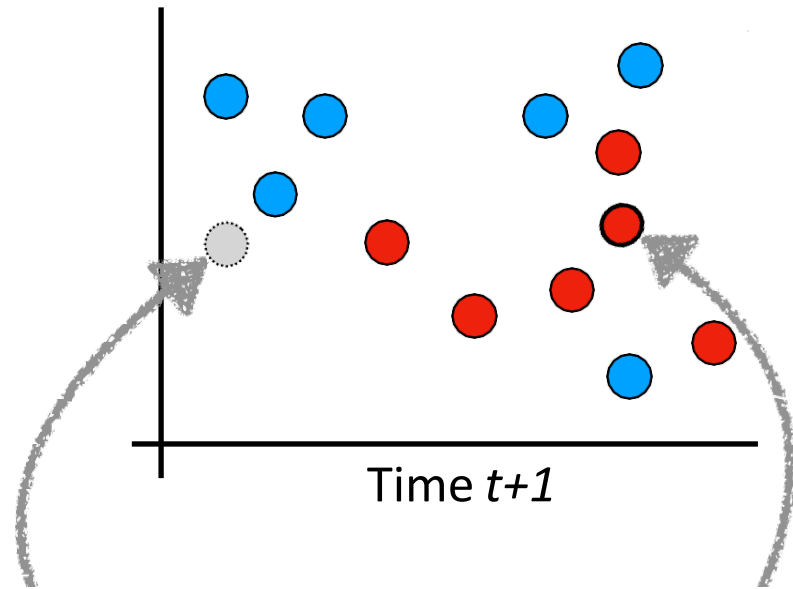
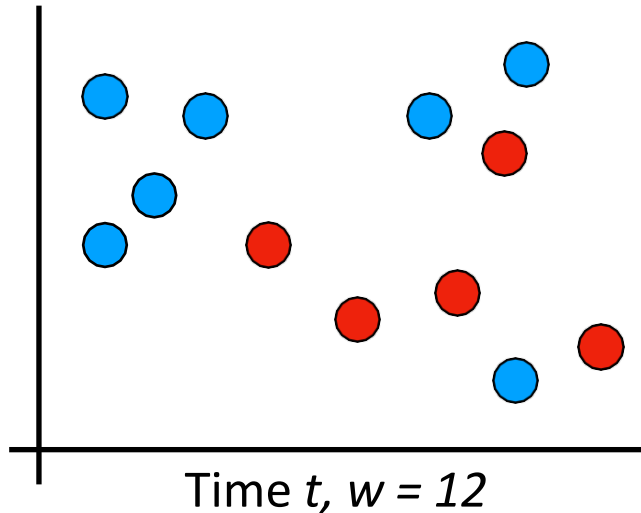
- The most common label of the  $k$  instances closer to a new instance determines its label
- The distance between instances is calculated (commonly) using the Euclidean Distance:

$$d(a, b) = \sqrt{\sum_{i=1}^m (a_i - b_i)^2}$$



# Online K-Nearest Neighbours (KNN)

- Use a fixed size sliding window to save the instances



Forgot the oldest instance

Latest instance added







Bifet, A., Pfahringer, B., Read, J., & Holmes, G. **Efficient data stream classification via probabilistic adaptive windows**. ACM symposium on applied computing, 2013

# Online KNN with ADWIN (KNN-ADWIN)

- If a concept drift occurs, with KNN there is the risk that the instances saved into the window belong to the old concept
- Use ADWIN to automatically set the size of the sliding window to save the instances

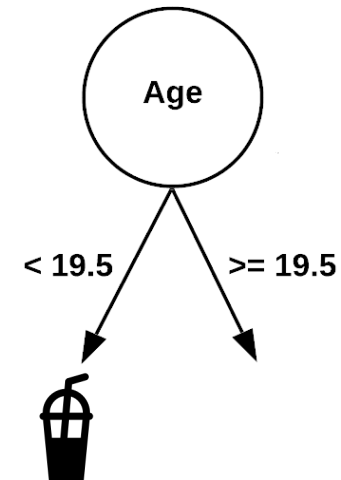
# Decision Trees

## Recommending drinks

Gender	Age	Drink
F	13	
M	13	
F	23	
M	32	
F	42	
M	16	

Which feature best determines the drink?

➤ **Age**









[https://en.wikipedia.org/wiki/Decision\\_tree\\_learning](https://en.wikipedia.org/wiki/Decision_tree_learning)



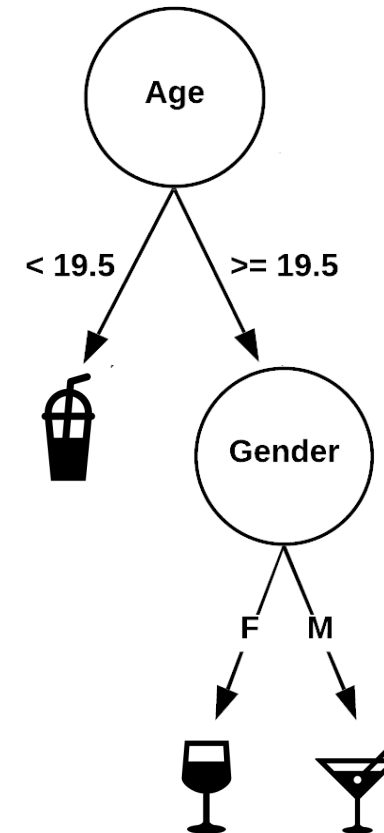
# Decision Trees

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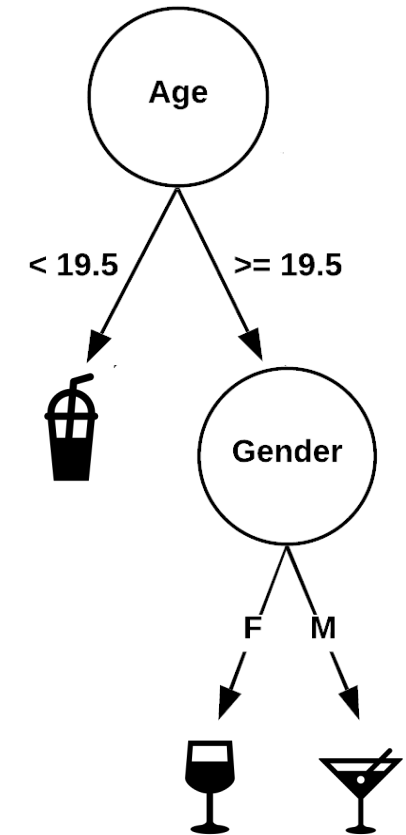
➤ **Age**



[https://en.wikipedia.org/wiki/Decision\\_tree\\_learning](https://en.wikipedia.org/wiki/Decision_tree_learning)

# Decision Trees

- Each node tests a features
- Each branch represents a value
- Each leaf assigns a class
- Greedy recursive induction:
  - Sort all examples through tree
  - $X_i$  = most discriminative attribute using the Gini index or Information Gain (H)
  - New node for  $X_i$ , new branch for each value, leaf assigns majority class
  - Stop if no error or limit on #instances



[https://en.wikipedia.org/wiki/Decision\\_tree\\_learning](https://en.wikipedia.org/wiki/Decision_tree_learning)

# Hoeffding Trees (VFDT)

- Build the decision tree incrementally
- The final tree must be identical (with high probability) to a tree built using a batch decision tree algorithm
- With theoretical guarantees on the error rate



src: <https://www.bilibili.tv/en/video/4787736782838275>

Pedro Domingos and Geoff Hulten. **Mining high-speed data streams**. 2000

# Hoeffding Trees (VFDT)

- Which attribute to choose at each splitting node?
- A small sample can often be enough to choose the optimal splitting attribute
  - Collect sufficient statistics from a small set of examples
  - Estimate the merit of each attribute
- How large should be the sample?
  - **Fixed size:** defined *a-priori* without looking for the data



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- A small sample can often be enough to choose the optimal splitting attribute
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- How large should be the sample?
  - ✗ ➤ **Fixed size:** defined *a-priori* without looking for the data
  - ✓ ➤ **Moving size:** Choose the sample size that allow to differentiate between the alternatives.



src: <https://www.bilibili.tv/en/video/4787736782838275>

Pedro Domingos and Geoff Hulten. **Mining high-speed data streams.** 2000

# Hoeffding Trees (VFDT)

- **Moving size:** Use Hoeffding bound to guarantee that the best attribute is really the best:

- Let  $X_1$  and  $X_2$  be, respectively, the two most informative attribute

- Split if:  $H(x_1) - H(x_2) > \varepsilon = \sqrt{\frac{R^2 * \log(1/\delta)}{2N}}$

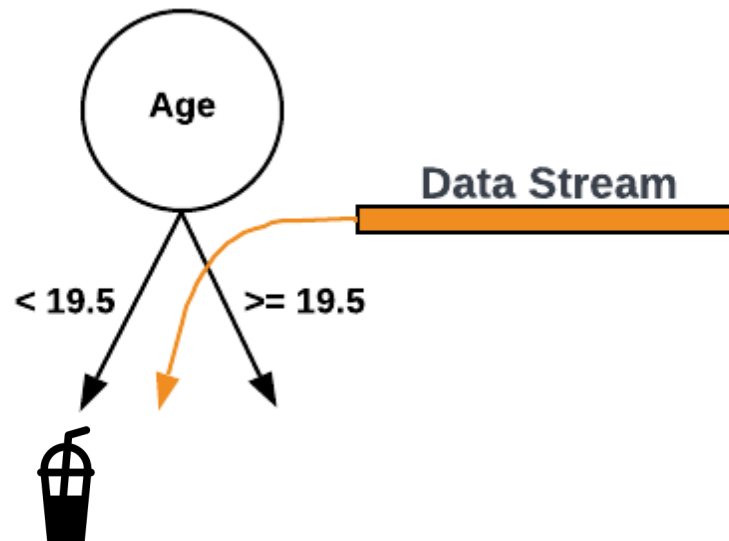
where  $R$  is the  $H$  range,  $\delta$  is the confidence bound and  $N$  is the number of instances seen by that node



src: <https://www.bilibili.tv/en/video/4787736782838275>

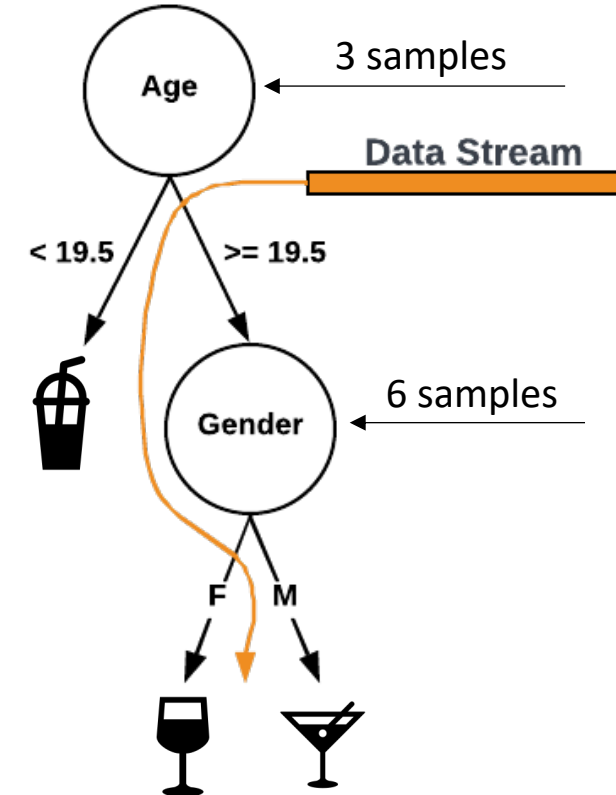
Pedro Domingos and Geoff Hulten. **Mining high-speed data streams.** 2000

# Hoeffding Trees (VFDT)



$$H(\text{Gender}) - H(\text{Age}) > \varepsilon$$

$$\varepsilon = \sqrt{\frac{R^2 * \log(1/\delta)}{2N}}$$



**Attributes:**      **Label: Drink**

- Age
  - Gender
-

# Concept Adapting VFDT (CVFDT)

- What happens when a **concept drift** occurs?
  - The nodes are no longer representative of the current concept
- CVFDT keeps its model consistent with a sliding window of  $w$  samples
- It constructs “alternative branches” as preparation for changes
- If the alternative branch becomes more accurate, switch of tree branches

## Cons:

- No theoretical guarantees on the error rate of CVFDT
- $W$  is fixed

G. Hulten, L. Spencer, and P. Domingos. **Mining time-changing data streams**. 2001



src: <https://giphy.com/gifs/dance-dancing-groot-JwTqLNfrx4OPe>



# Hoeffding Adaptive Tree (HAT)

- Replace frequency statistics counters by estimators
  - Don't need a window to store examples, since it maintains the statistics data needed with estimators
- Change the way of checking the substitution of alternate subtrees, using a change detector with theoretical guarantees (ADWIN)
  - Keeps sliding window consistent with the *no-change hypothesis*

## Pro:

- Theoretical guarantees
- No Parameters



A. Bifet, R. Gavald`a. **Adaptive Parameter-free Learning from Evolving Data Streams**. IDA, 2009

# CASH problem and AutoML

CASH problem: **C**ombined **A**lgorithm **S**election and **H**yperparameter.

AutoML aims to automate the data mining pipeline:

- Data cleaning
- Feature engineering
- Algorithm selection
- Hyperparameters tuning

Different implementations with different search spaces and hyperparameter optimizations:

- Auto Weka 2.0
- Autotklearn
- TPOT
- GAMA
- H2O



src: <https://www.pexels.com/it-it/foto/radio-a-transistor-grigia-e-nera-157557/>

# CASH problem with SML

CASH solution does not consider the adaptation of parameters in an evolving data stream.

Actual applications to a streaming scenario:

- Train AutoML only on the first portion of the data stream
- Retrain AutoML from scratch after a concept drift
- Computational expensive
- Large number of parallel trainings
- Only consider algorithm selection

# EvoAutoML

- It naturally adapts the population of algorithms and configurations
- It avoids expensive retraining
- It addresses the Online CASH problem by finding the joint algorithm combination and hyperparameter setting that minimizes a predefined loss over a stream of data

It considers:

- Pipeline structure
- Algorithms
- Configuration space
- It makes predictions by majority voting

C. Kulbach, J. Montiel, M. Bahri, M. Heyden, & A. Bifet. **Evolution-Based Online Automated Machine Learning**. PAKDD, 2022



# Exercise 3: Stream Classification





# Credits

- Albert Bifet DATA STREAM MINING 2020-2021 course at Telecom Paris
- Alessio Bernardo & Emanuele Della Valle

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