



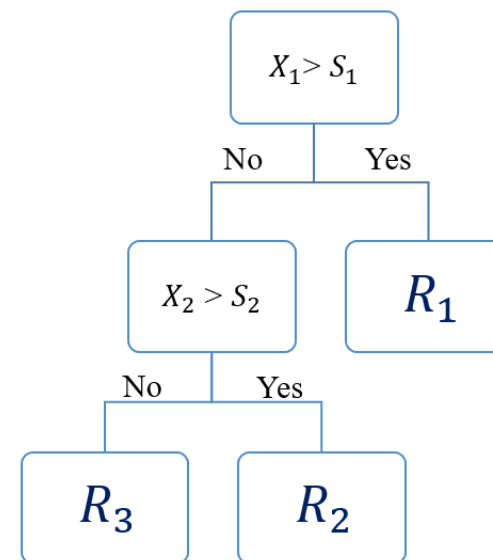
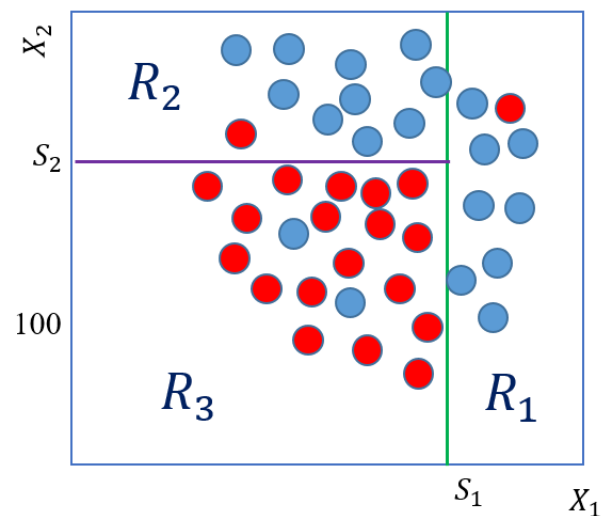
Module 9

Classification and Regression Trees

CART



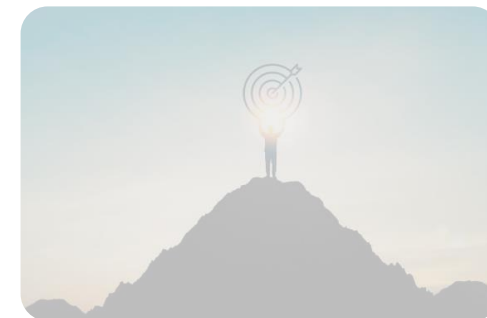
Prof. Pedram Jahangiry





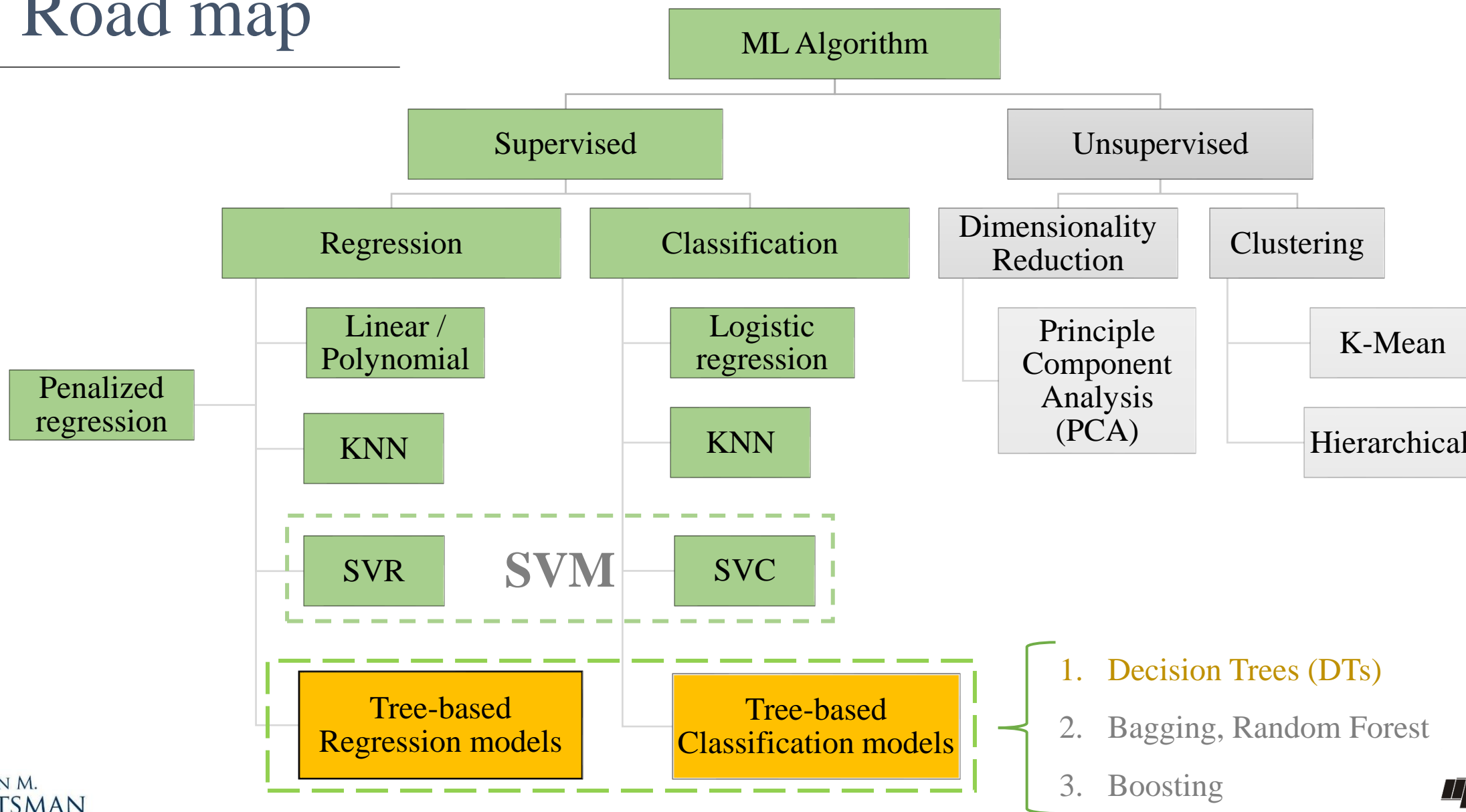
Class Modules

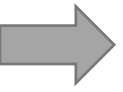
- Module 1- Introduction to Deep Learning
- Module 2- Setting up Machine Learning Environment
- Module 3- Linear Regression (Econometrics approach)
- Module 4- Machine Learning Fundamentals
- Module 5- Linear Regression (Machine Learning approach)
- Module 6- Penalized Regression (Ridge, LASSO, Elastic Net)
- Module 7- Logistic Regression
- Module 8- K-Nearest Neighbors (KNN)
- **Module 9- Classification and Regression Trees (CART)**
- Module 10- Bagging and Boosting
- Module 11- Dimensionality Reduction (PCA)
- Module 12- Clustering (KMeans – Hierarchical)





Road map





Topics

Part I

1. Decision Trees Definitions
2. Decision Trees criteria
 - MSE
 - Error Rate
 - Gini Index
 - Entropy

Part II

1. Regression Trees
2. Classification Trees

Part III

1. Pruning a tree
2. Hyperparameters

Part IV

1. Pros and Cons
2. Applications in Finance

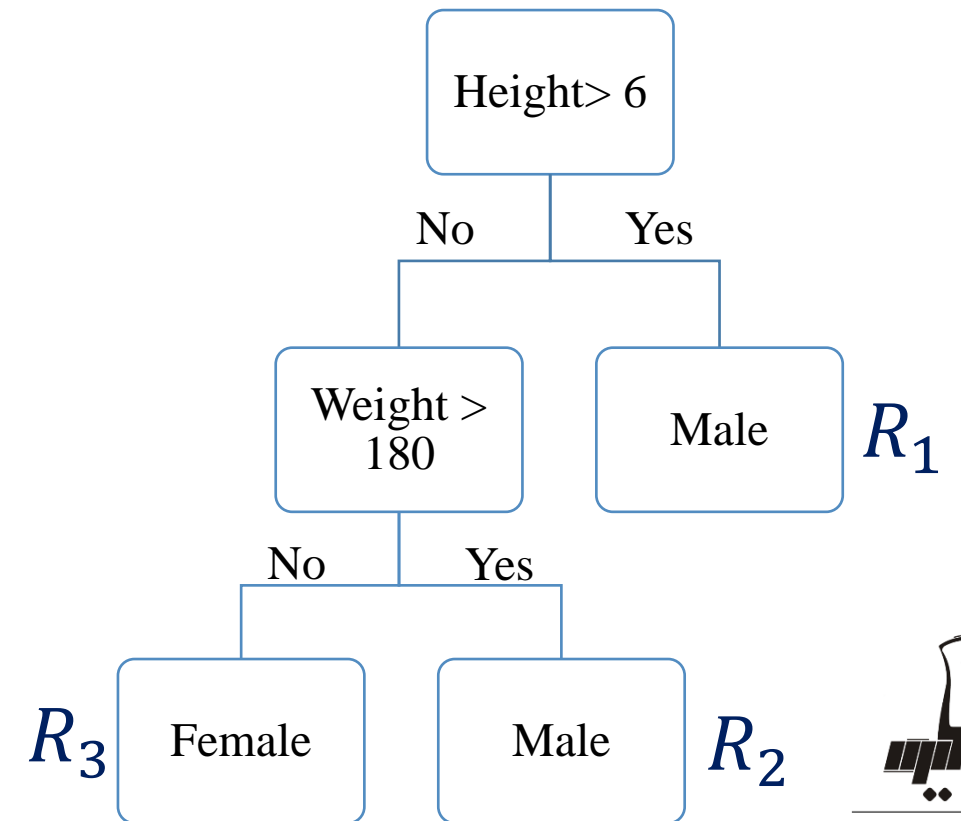
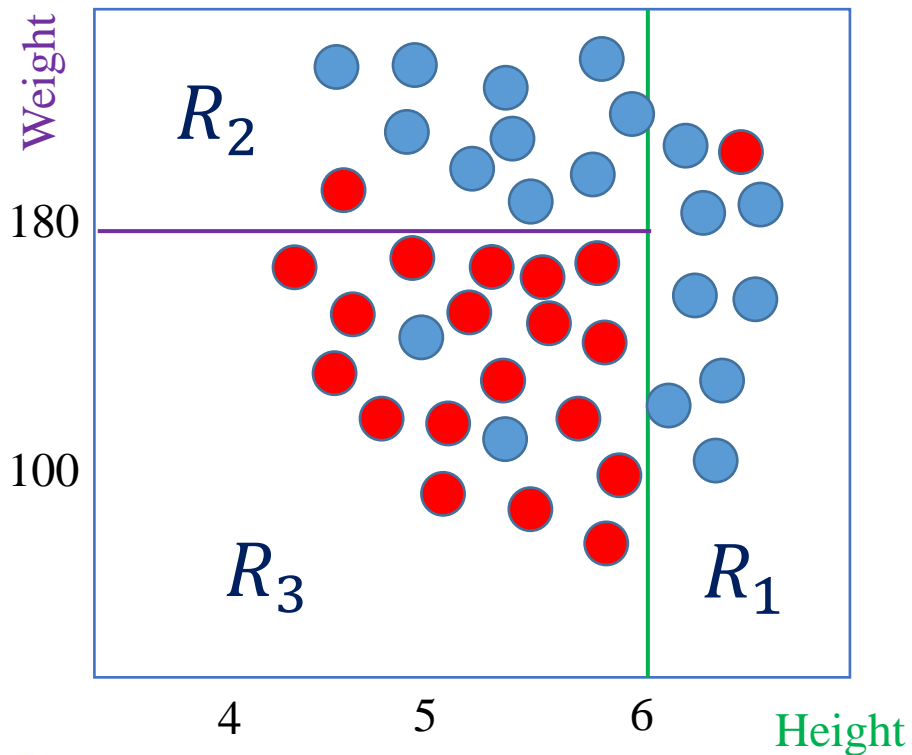


Part I

Decision Trees definitions and criteria

Decision Trees Definitions

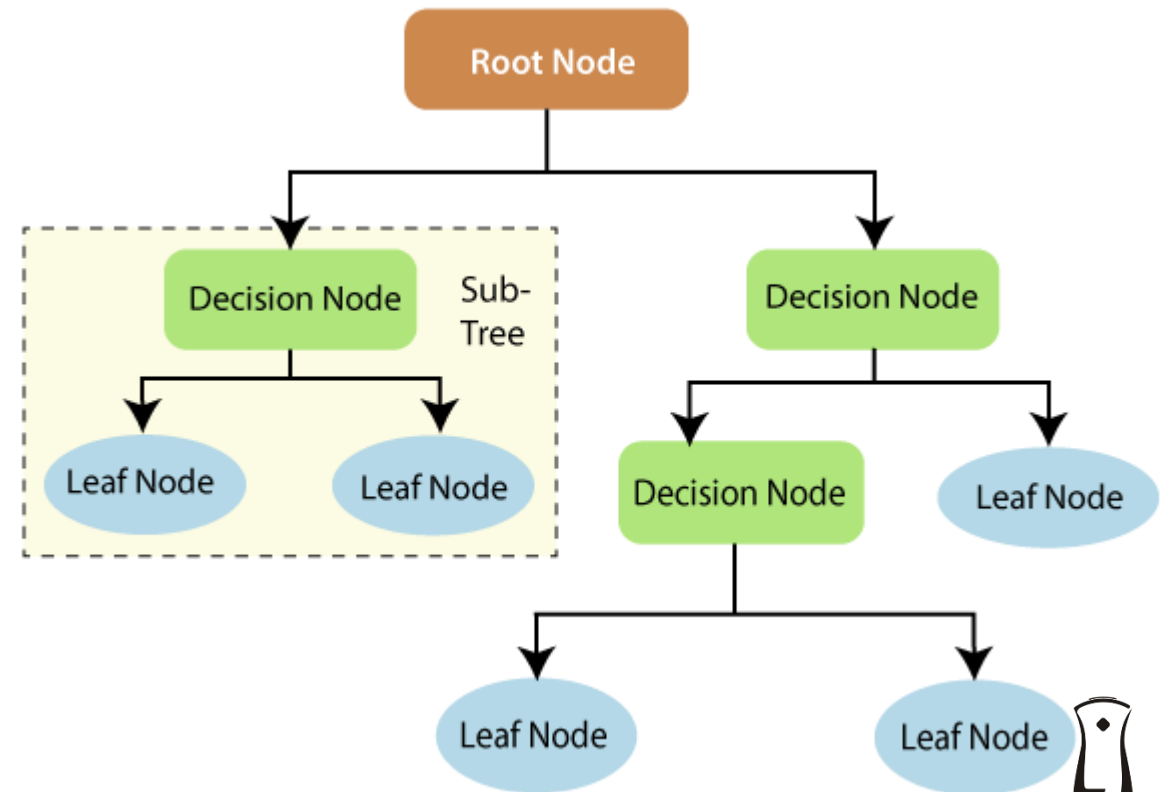
- DTs are ML algorithms that progressively divide data sets into smaller data groups based on a descriptive feature, until they reach sets that are small enough to be described by some label.
- DTs apply a top-down approach to data, trying to group and label observations that are similar.



Decision Trees Definitions

- When the target variable consists of **real numbers**: **regression** trees
- When the target variable is **categorical**: **classification** trees
- Terminology:

- ✓ Root node
- ✓ Splitting
- ✓ Branch
- ✓ Decision node (internal node)
- ✓ Leaf node (terminal node)
- ✓ Sub-tree
- ✓ Depth (level)
- ✓ Pruning

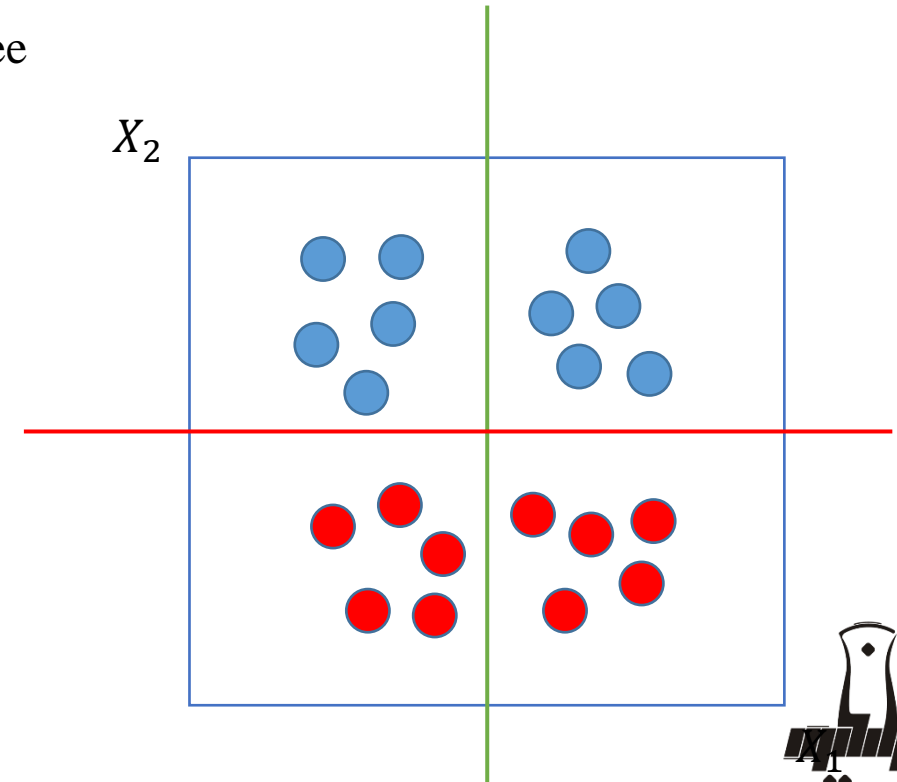


→ Decision Trees Criteria

- Which split adds the most information gain (minimum impurity)?
- Regression trees: MSE
- Classification trees:
 1. Error rate
 2. Entropy
 3. Gini Index

Control how a Decision Tree decides to **split** the data

They all measure
impurity

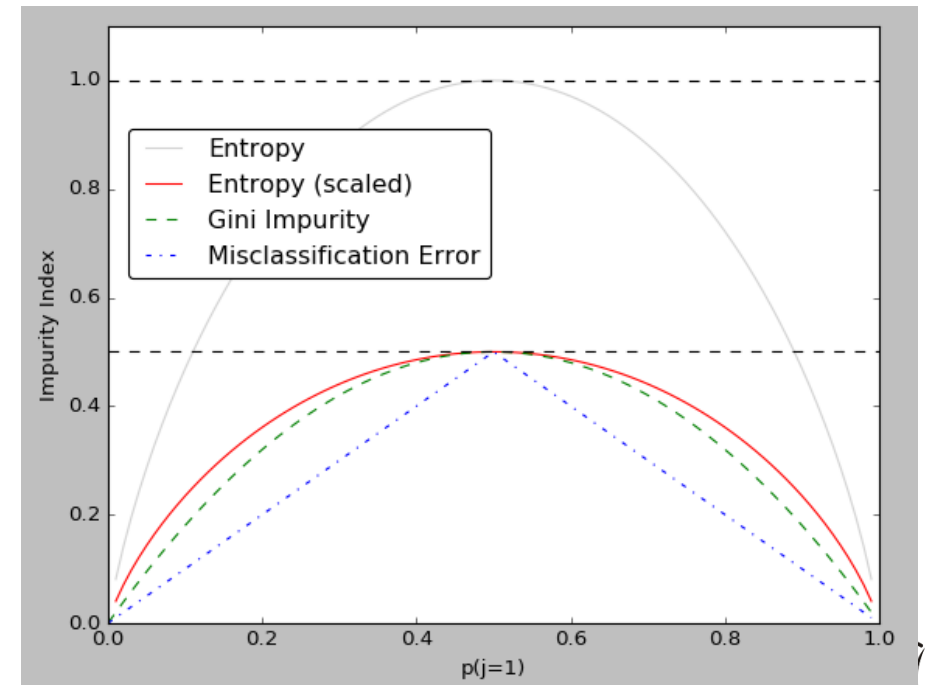


Decision Trees Criteria

- **Entropy**: Measures the impurity or randomness (uncertainty) in the data points
- **Gini Index**: Measure how often a randomly chosen element would be incorrectly labeled
- For both Entropy and Gini, 0 expresses all the elements belong to a specified class (**pure**)
- Different decision tree algorithms utilize different impurity metrics

$$\text{entropy} = - \sum_j p_j \log_2(p_j)$$

$$\text{Gini} = 1 - \sum_j p_j^2$$



Part II

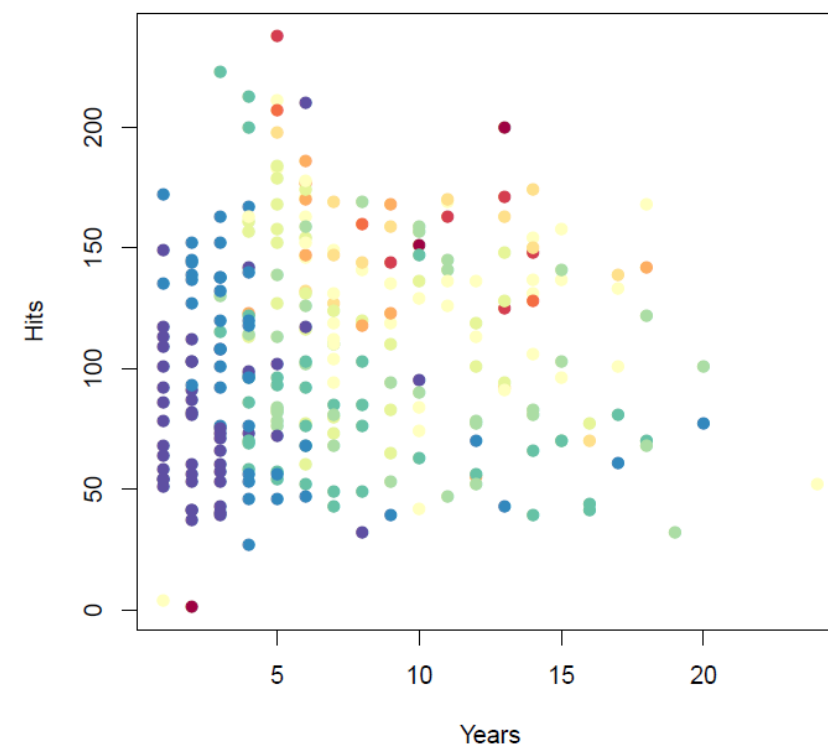
Regression / Classification Trees!

How does a decision tree work?



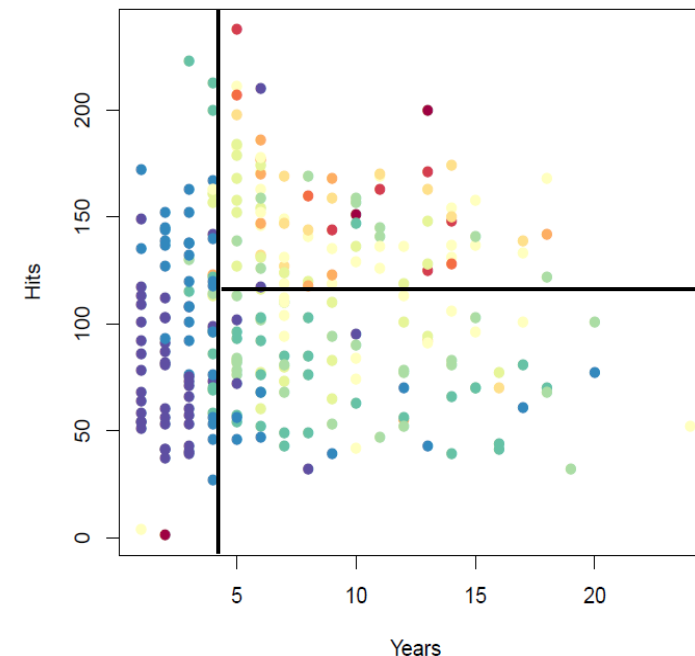
Regression Trees

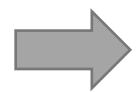
- Baseball Salary is color-coded from low (blue, green) to high (yellow, red)
- DTs apply a top-down approach to data, trying to group and label observations that are similar.
- The main questions in every decision-making process:
 1. Which feature to start with?
 2. Where to put the split (cut off)?



➔ Interpreting the results

- Based on color-coded salary, it seems that **years** is the most important factor in determining **salary**.
- For less experienced players, the number of **hits** seems irrelevant.
- Among more experienced players though, players with more **hits** tend to have higher **salaries**.
- As one can see, the model is very **easy to display, interpret and explain**.



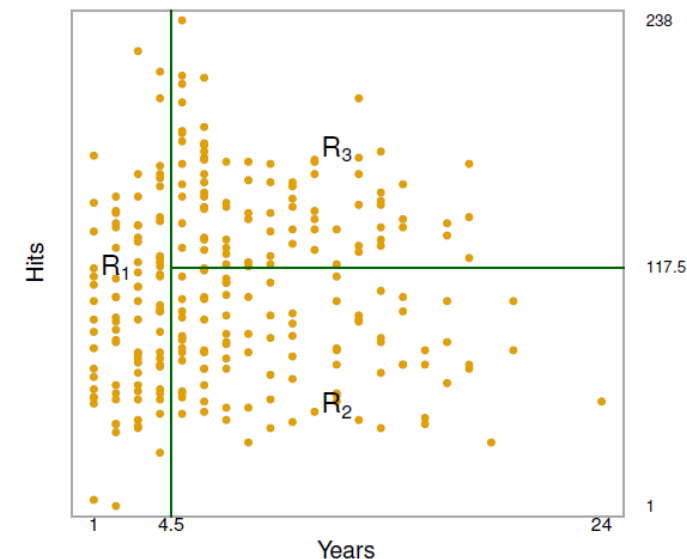


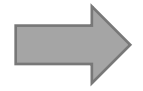
Tree building process

- Divide the feature space into **J distinct** and **non-overlapping** regions.
- For every observation that falls into the region R_j , we make the **same prediction**, which is simply the **mean of the target values** for the training observations in R_j .
- The goal is to find rectangles R_1, R_2, \dots, R_J that **minimize the RSS**:

$$\sum_{j=1}^J \sum_{i \in R_j} (y_i - \hat{y}_{R_j})^2$$

- Where \hat{y}_{R_j} is the mean target for the training observations within the j^{th} rectangle.





Tree building process: Recursive Binary Splitting

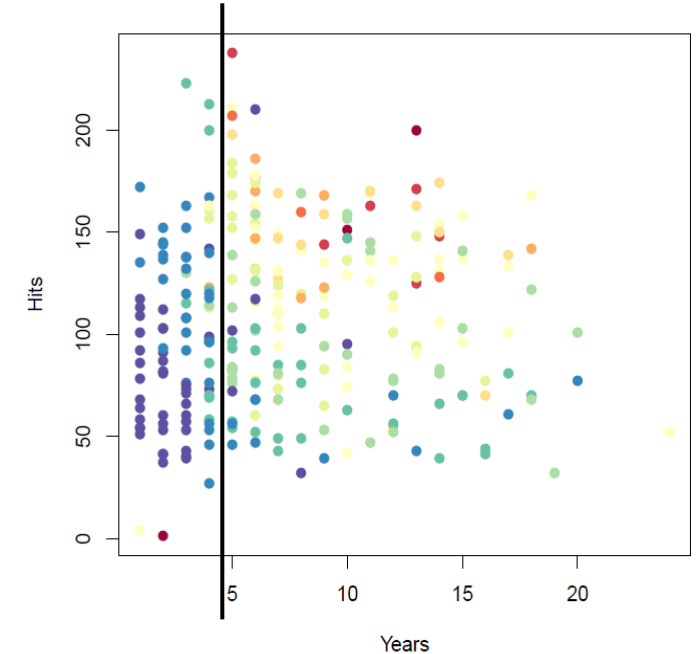
- How does the algorithm select X_j and the split s ?
- X_j and s are selected such that splitting the feature space into the regions $\{X|X_j < s\}$ and $\{X|X_j \geq s\}$ leads to the largest possible reduction in RSS.

$$R_1(j, s) = \{X|X_j < s\} \text{ and } R_2(j, s) = \{X|X_j \geq s\}$$

- Seeking for the value of j and s that minimized the following equation:

$$\sum_{i: x_i \in R_1(j, s)} (y_i - \hat{y}_{R_1})^2 + \sum_{i: x_i \in R_2(j, s)} (y_i - \hat{y}_{R_2})^2$$

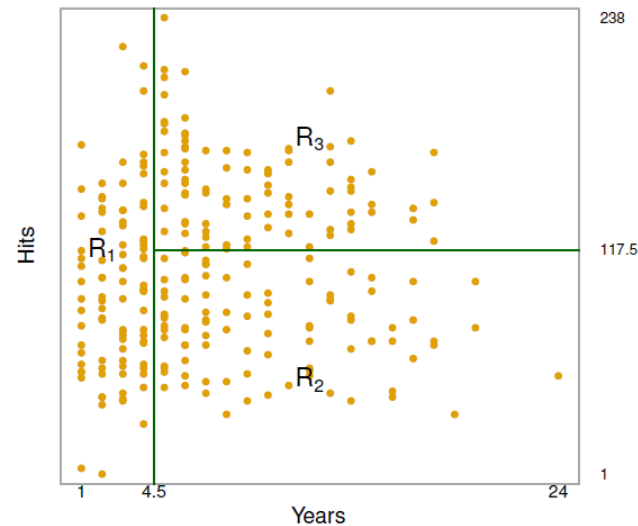
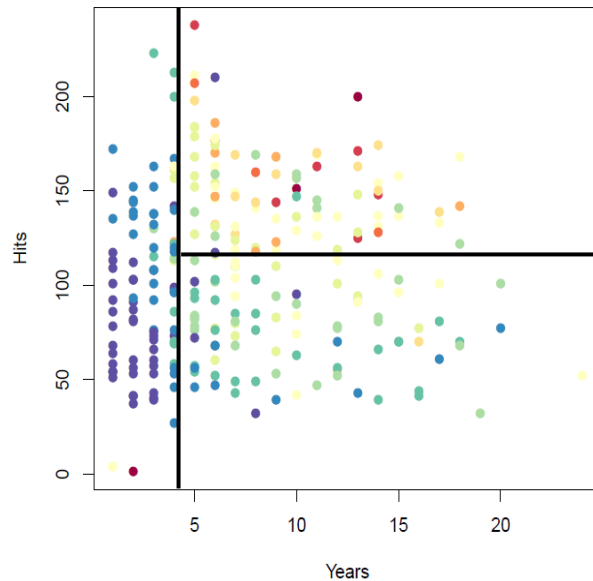
- The **best split** is made at that particular step, rather than **looking ahead** and picking a split that will lead to a better tree in some **future step**.

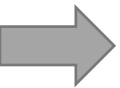




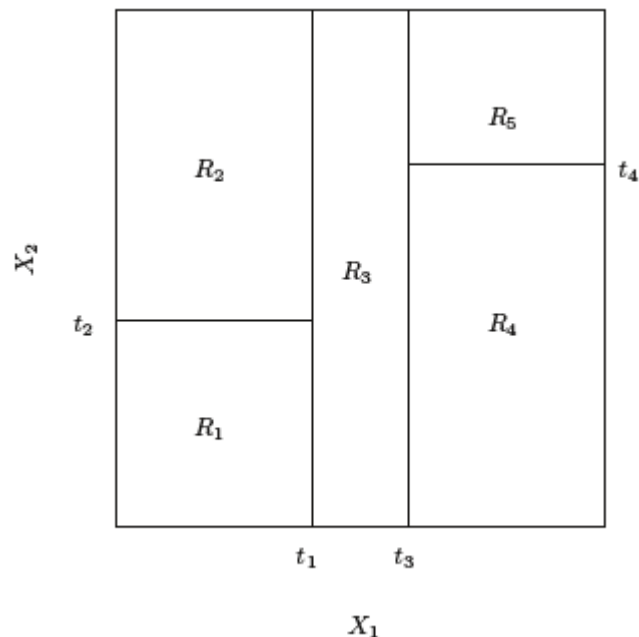
Tree building process: Recursive Binary Splitting

- Next, the algorithm repeats the process, looking for the **best feature and best split** in order to split the data further **to minimize the RSS within each of the resulting regions**.
- The process continues **until a stopping criterion** is reached; for instance, continues until no region contains more than a fixed number of observations.

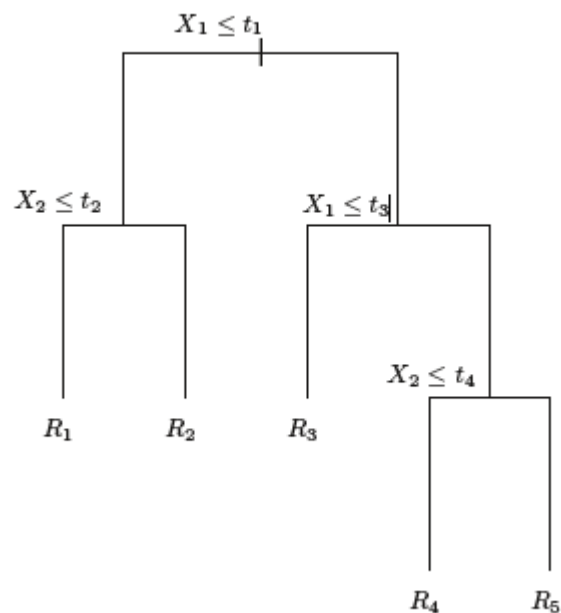




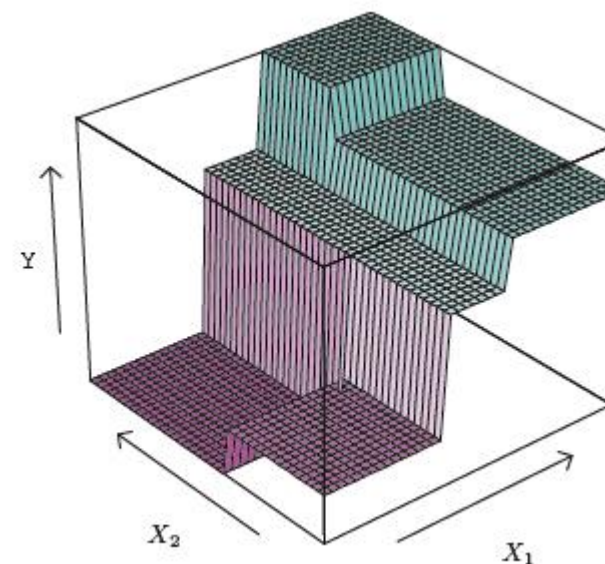
A Five-Region Example of Recursive Binary Splitting



The output of **recursive binary splitting** on a two-dimensional example



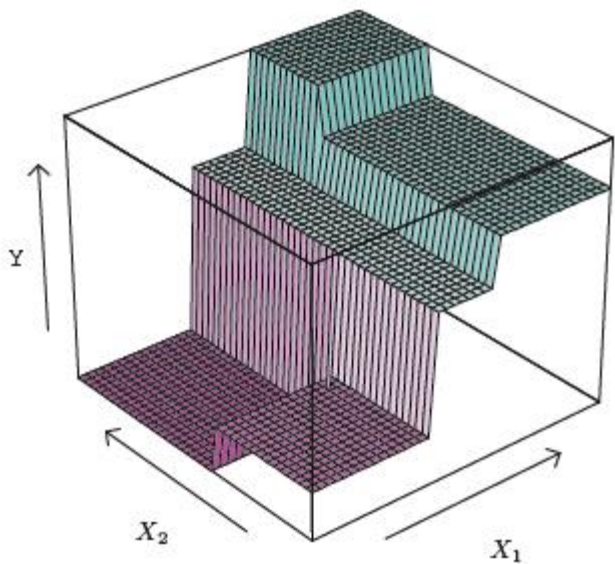
A tree corresponding to the partition in the left panel.



A perspective plot of the prediction surface corresponding to that tree.

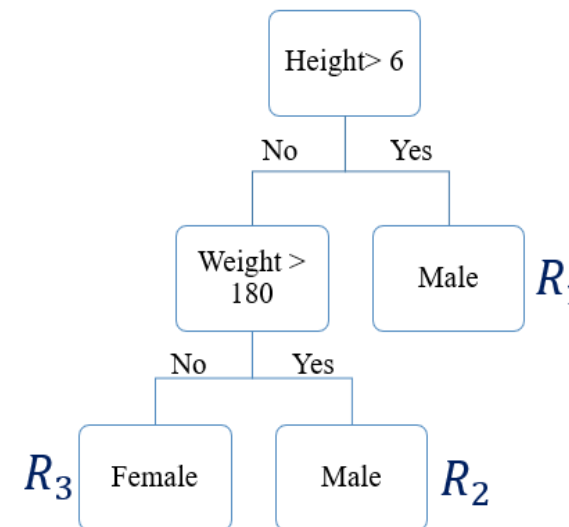
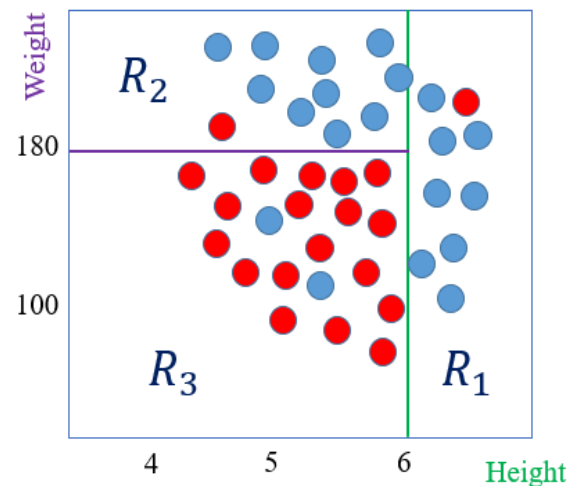


Overfitting?



→ Classification Trees

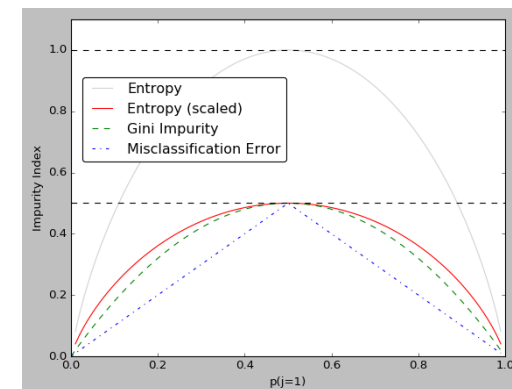
- Classification trees are very similar to regression trees, except that it is used to predict a **qualitative** response rather than a **quantitative** one.
- The prediction of the algorithm at each terminal node will be the category with the majority of data points i.e., the **most commonly occurring class**.



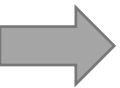
→ Classification Trees (details)

- Just as in the regression setting, the **recursive binary splitting** is used to grow a classification tree. However, instead of RSS we will be using one of the following impurity criteria:

1. Classification error rate: $\longrightarrow E = 1 - \max_k(\hat{p}_{mk})$
2. Gini index: $\longrightarrow G = \sum_{k=1}^K \hat{p}_{mk}(1 - \hat{p}_{mk})$
3. Cross entropy: $\longrightarrow D = - \sum_{k=1}^K \hat{p}_{mk} \log \hat{p}_{mk}$

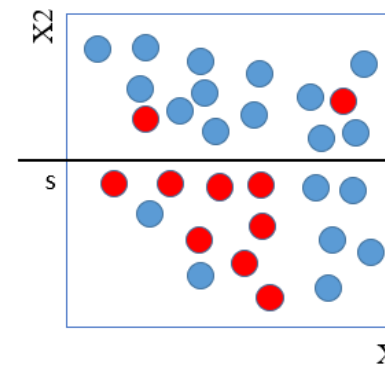
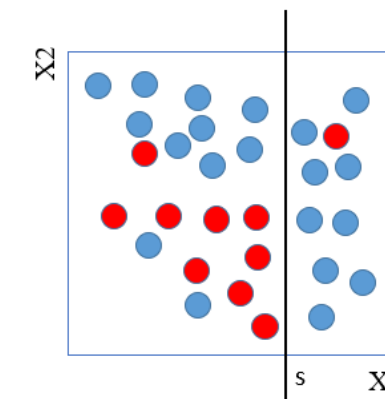
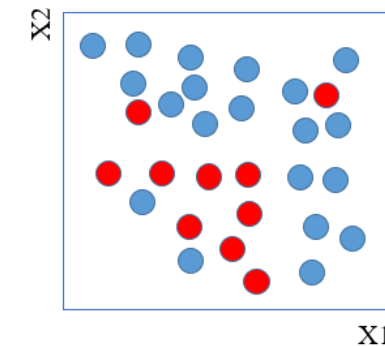


- \hat{p}_{mk} represents the proportion of training observations in the m^{th} region from the k^{th} class.
- Classification error rate is **not sufficiently sensitive to node purity** and in practice either **Gini** or **Cross entropy** is preferred.



Decision Tree Metrics (Simple Example)

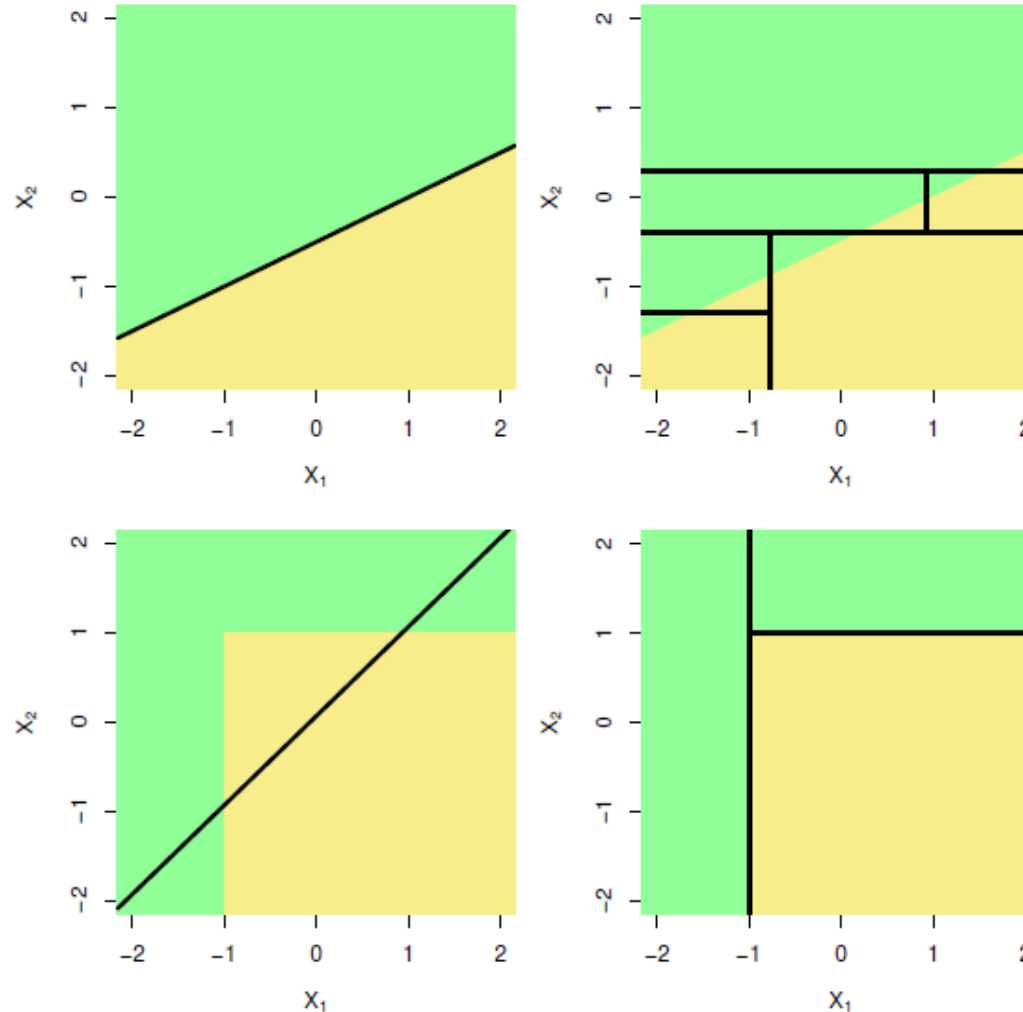
<i>Node</i>	<i>Gini</i> $1 - \sum_j p_j^2$	<i>Cross entropy</i> $-\sum_j p_j \log(p_j)$	<i>Error rate</i> $1 - \max(p_i)$
Entire training data before split	$\left\{1 - \left(\left(\frac{10}{30}\right)^2 + \left(\frac{20}{30}\right)^2\right)\right\} = 0.44$	$-\left\{\left(\frac{10}{30} \log \frac{10}{30} + \frac{20}{30} \log \frac{20}{30}\right)\right\} = 0.64$	$1 - \max\left\{\frac{10}{30}, \frac{20}{30}\right\}$ $= 1 - \frac{20}{30} = 0.333$



→ Trees Versus Linear Models

Left column: linear model; Right column: tree-based model

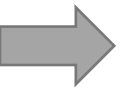
Top Row: True linear boundary
Bottom row: true non-linear boundary.



Part III

Pruning a tree

Tunning hyper parameters

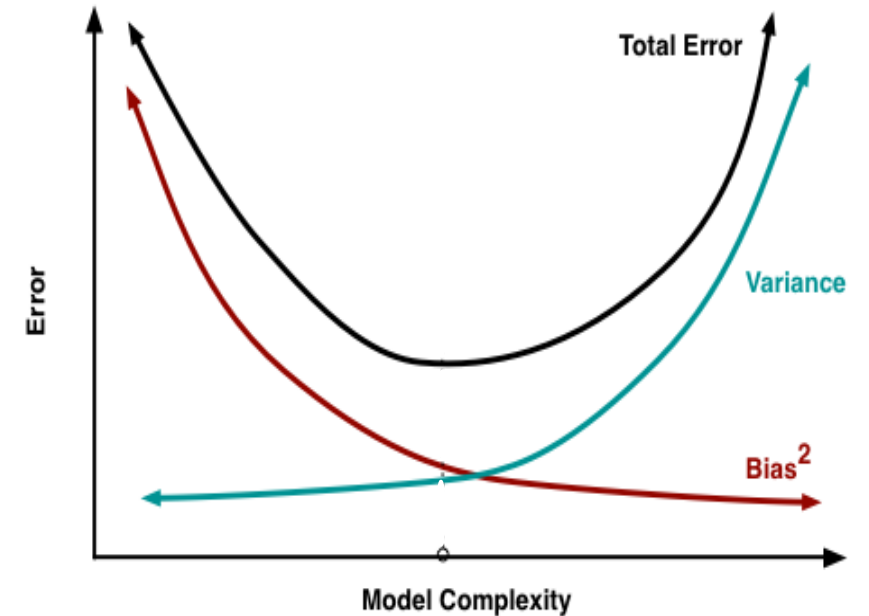


Pruning a tree

- A **smaller tree** with fewer splits may lead to **lower variance** and better interpretation (but) at the cost of **higher bias**.
- Smaller trees are too short-sighted:

*“ a **seemingly worthless** split early on in the tree might be followed by a **very good split**, a split that leads to a large reduction in RSS/impurity index later on”*

- A better strategy is to **grow a very large tree**, this may produce good predictions on the training set, but is likely to overfit the data, leading to poor test set performance.
- So, we need to prune it back in order to obtain a subtree.
- **Cost complexity pruning** is used to do this.





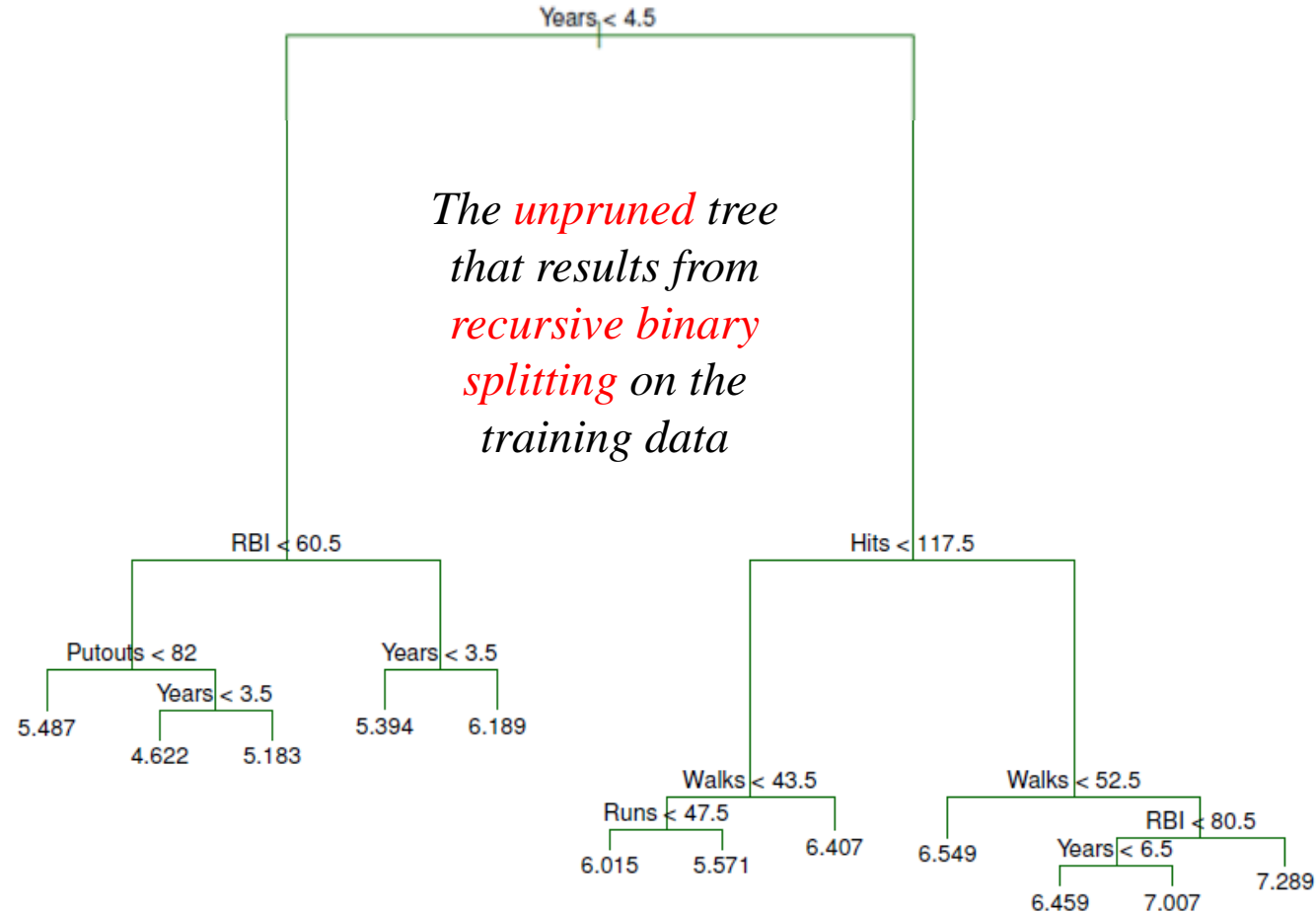
Cost complexity pruning (weakest link pruning)

- Consider a sequence of trees indexed by a **nonnegative tuning parameter α** .
- For each value of α there corresponds a **subtree $T \subset T_0$** such that the following objective function is minimized.

$$\sum_{m=1}^{|T|} \sum_{i: x_i \in R_m} (y_i - \hat{y}_{R_m})^2 + \alpha |T|$$

- $|T|$ indicates the number of terminal nodes of the tree T
 - R_m is the rectangle corresponding to m^{th} terminal node and
 - \hat{y}_{R_m} is the mean of the training observations in R_m
-
- α controls **the bias variance trade off** and is determined by **cross validation**.
 - Lastly, we return to full data set and obtain the subtree corresponding to α

Salary example continued



➔ Finding the optimal α or T

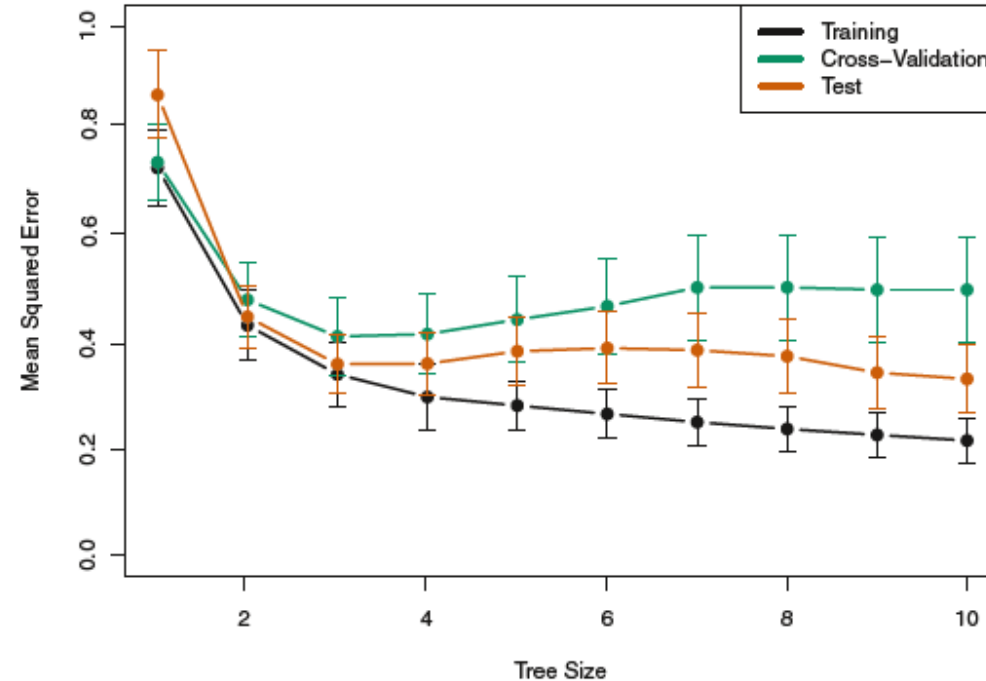
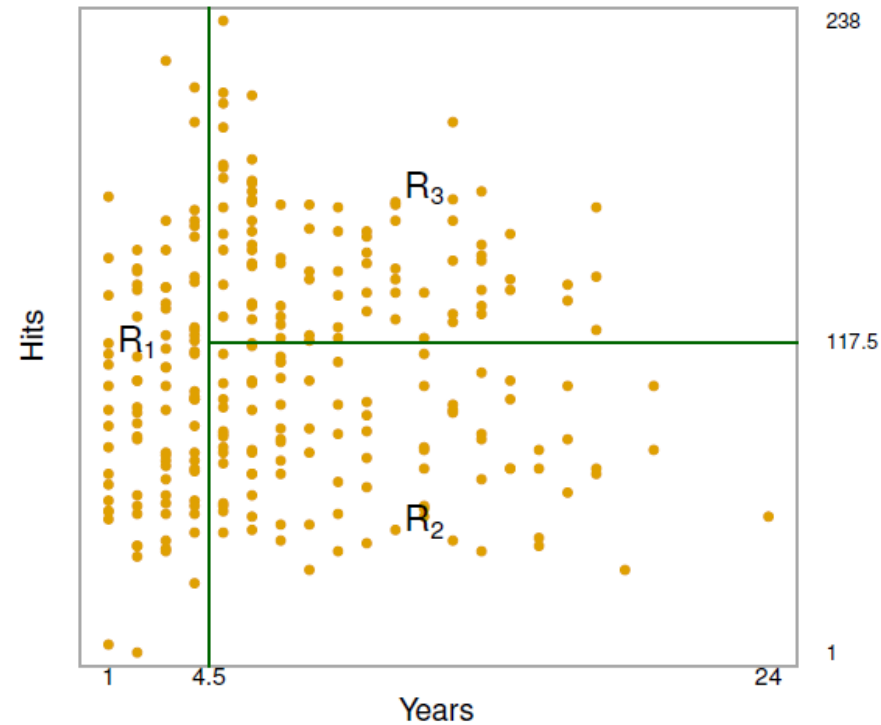
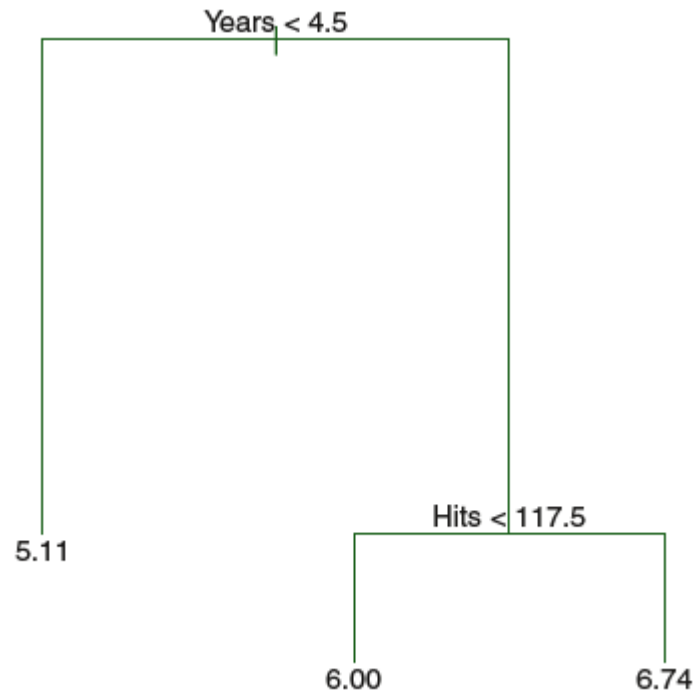


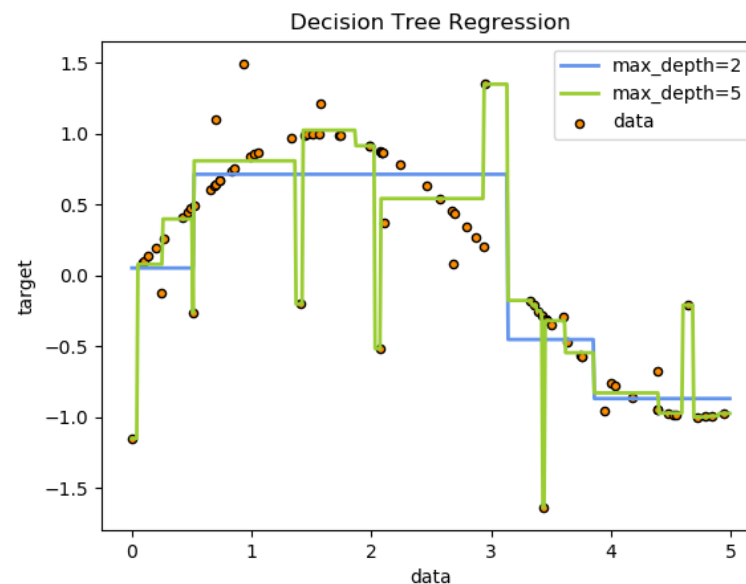
FIGURE 8.5. Regression tree analysis for the **Hitters** data. The training, cross-validation, and test MSE are shown as a function of the number of terminal nodes in the pruned tree. Standard error bands are displayed. The minimum cross-validation error occurs at a tree size of three.

➔ The optimal (pruned) tree



➔ Other hyperparameters

- ✓ To avoid overfitting, **regularization parameters** can be added to the model such as:
 - Maximum depth of the tree
 - Minimum population at a node
 - Maximum number of decision nodes
 - Minimum impurity decrease (info gain)
 - Alpha (complexity parameter)
- ✓ Other hyperparameters are:
 - Criterion: gini, entropy
 - Splitter: best, random
 - Class weight: balanced, none



Part IV

Pros and Cons

Applications in finance



DTs' Pros and Cons



Pros:

- Easy to interpret and visualize
- Can easily handle categorical data without the need to create dummy variables
- Can easily capture Non-linear patterns
- Can handle data in its raw form (no preprocessing needed). Why?
- Has no assumptions about distribution because of the non-parametric nature of the algorithm

Cons:

- Poor level of predictive accuracy.
- Sensitive to noisy data. It can overfit noisy data. Small variations in data can result in the different decision tree*.

*This can be reduced by bagging and boosting algorithms.

→ DTs' Applications in finance

- Enhancing detection of fraud in financial statements,
- Generating consistent decision processes in equity and fixed-income selection
- Simplifying communication of investment strategies to clients.
- Portfolio allocation problems.



Parameter	Description	Default	Options
max_depth	The maximum number of levels: split the nodes until max_depth has been reached. All leaves are pure or contain fewer samples than min_samples_split.	None	int
max_features	Number of features to consider for a split.	None	None: all features int: # features float: fraction auto, sqrt: sqrt(n_features) log2: log2(n_features)
max_leaf_nodes	Split nodes until creating this many leaves.	None	None: unlimited int
min_impurity_decrease	Split node if impurity decreases by at least this value.	0	float
min_samples_leaf	A split will only be considered if there are at least min_samples_leaf training samples in each of the left and right branches.	1	int; float (as a percent of N)
min_samples_split	The minimum number of samples required to split an internal node.	2	int; float (percent of N)
min_weight_fraction_leaf	The minimum weighted fraction of the sum total of all sample weights needed at a leaf node. Samples have equal weight unless sample_weight is provided in the fit method.	0	

Appendix A

Scikit-Learn decision tree parameters.



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