Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   Ensembles   Summary

○○○○○○○○○○○○○○○○○○○○

Information-based Learning

Sections 4.4, 4.5

John D. Kelleher and Brian Mac Namee and Aoife D'Arcy

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   Ensembles   Summary

○○○○○○○○○○○○○○○○○○○○○

1 **Alternative Feature Selection Metrics**

2 **Handling Continuous Descriptive Features**

3 **Predicting Continuous Targets**

4 **Noisy Data, Overfitting and Tree Pruning**

5 **Model Ensembles**
- Bagging
- Boosting
- Gradient Boosting

6 **Summary**

Alternative Feature Selection Metrics

- Entropy based information gain, preferences features with many values.
- One way of addressing this issue is to use **information gain ratio** which is computed by dividing the information gain of a feature by the amount of information used to determine the value of the feature:

$$GR(d, \mathcal{D}) = \frac{IG(d, \mathcal{D})}{-\sum\limits_{l \in levels(d)} (P(d = l) \times log_2(P(d = l)))} \quad (1)$$

$$IG(\text{STREAM}, \mathcal{D}) = 0.3060$$
$$IG(\text{SLOPE}, \mathcal{D}) = 0.5774$$
$$IG(\text{ELEVATION}, \mathcal{D}) = 0.8774$$

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   Ensembles   Summary

○○○○○○○○○○○○○○○○○○○○

$H\left(\text{STREAM}, \mathcal{D}\right)$

$$= -\sum_{l \in \left\{\begin{smallmatrix} true, \\ false \end{smallmatrix}\right\}} P(\text{STREAM} = l) \times log_2\left(P(\text{STREAM} = l)\right)$$

$$= -\left(\left(^4/_7 \times log_2(^4/_7)\right) + \left(^3/_7 \times log_2(^3/_7)\right)\right)$$

$$= 0.9852 \; bits$$

$H\left(\text{SLOPE}, \mathcal{D}\right)$

$$= -\sum_{l \in \left\{\begin{smallmatrix} flat, \\ moderate, \\ steep \end{smallmatrix}\right\}} P(\text{SLOPE} = l) \times log_2\left(P(\text{SLOPE} = l)\right)$$

$$= -\left(\left(^1/_7 \times log_2(^1/_7)\right) + \left(^1/_7 \times log_2(^1/_7)\right) + \left(^5/_7 \times log_2(^5/_7)\right)\right)$$

$$= 1.1488 \; bits$$

$H\left(\text{ELEVATION}, \mathcal{D}\right)$

$$= -\sum_{l \in \left\{\begin{smallmatrix} low, \\ medium, \\ high, \\ highest \end{smallmatrix}\right\}} P(\text{ELEVATION} = l) \times log_2\left(P(\text{ELEVATION} = l)\right)$$

$$= -\left(\left(^1/_7 \times log_2(^1/_7)\right) + \left(^2/_7 \times log_2(^2/_7)\right) + \left(^3/_7 \times log_2(^3/_7)\right) + \left(^1/_7 \times log_2(^1/_7)\right)\right)$$

$$= 1.8424 \; bits$$

$$GR\left(\textsc{Stream}, \mathcal{D}\right) = \frac{0.3060}{0.9852} = 0.3106$$

$$GR\left(\textsc{Slope}, \mathcal{D}\right) = \frac{0.5774}{1.1488} = 0.5026$$

$$GR\left(\textsc{Elevation}, \mathcal{D}\right) = \frac{0.8774}{1.8424} = 0.4762$$
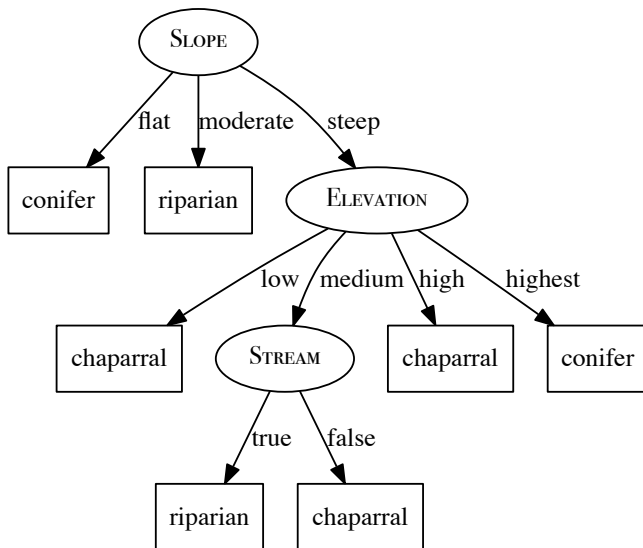
Figure 1: The vegetation classification decision tree generated using information gain ratio.

- Another commonly used measure of impurity is the **Gini index**:

$$Gini\,(t, \mathcal{D}) = 1 - \sum_{l \in levels(t)} P(t = l)^2 \qquad (2)$$

- The Gini index can be thought of as calculating how often you would misclassify an instance in the dataset if you classified it based on the distribution of classifications in the dataset.
- Information gain can be calculated using the Gini index by replacing the entropy measure with the Gini index.

$$Gini\,(\text{VEGETATION}, \mathcal{D})$$
$$= 1 - \sum_{l \in \left\{ \begin{array}{l} chapparal, \\ riparian, \\ conifer \end{array} \right\}} P(\text{VEGETATION} = l)^2$$
$$= 1 - \left((3/7)^2 + \left(2/7\right)^2 + \left(2/7\right)^2 \right)$$
$$= 0.6531$$

Table 1: Partition sets (Part.), entropy, Gini index, remainder (Rem.), and information gain (Info. Gain) by feature

Split by Feature	Level	Part.	Instances	Partition Gini Index	Rem.	Info. Gain
STREAM	*true*	$\mathcal{D}_1$	$\mathbf{d}_2, \mathbf{d}_3, \mathbf{d}_6, \mathbf{d}_7$	0.625	0.5476	0.1054
	false	$\mathcal{D}_2$	$\mathbf{d}_1, \mathbf{d}_4, \mathbf{d}_5$	0.4444		
SLOPE	*flat*	$\mathcal{D}_3$	$\mathbf{d}_5$	0	0.4	0.2531
	moderate	$\mathcal{D}_4$	$\mathbf{d}_2$	0		
	steep	$\mathcal{D}_5$	$\mathbf{d}_1, \mathbf{d}_3, \mathbf{d}_4, \mathbf{d}_6, \mathbf{d}_7$	0.56		
ELEVATION	*low*	$\mathcal{D}_6$	$\mathbf{d}_2$	0	0.3333	0.3198
	medium	$\mathcal{D}_7$	$\mathbf{d}_3, \mathbf{d}_4$	0.5		
	high	$\mathcal{D}_8$	$\mathbf{d}_1, \mathbf{d}_5, \mathbf{d}_7$	0.4444		
	highest	$\mathcal{D}_9$	$\mathbf{d}_6$	0		

Handling Continuous Descriptive Features

- The easiest way to handle continuous valued descriptive features is to turn them into boolean features by defining a threshold and using this threshold to partition the instances based their value of the continuous descriptive feature.
- How do we set the threshold?

1. The instances in the dataset are sorted according to the continuous feature values.
2. The adjacent instances in the ordering that have different classifications are then selected as possible threshold points.
3. The optimal threshold is found by computing the information gain for each of these classification transition boundaries and selecting the boundary with the highest information gain as the threshold.

- Once a threshold has been set the dynamically created new boolean feature can compete with the other categorical features for selection as the splitting feature at that node.
- This process can be repeated at each node as the tree grows.

Feature Selection   **Cont. Desc. Features**   Cont. Targets   Noise and Overfitting   Ensembles   Summary

○○○○○○○○○○○○○○○○○○○○○○

Table 2: Dataset for predicting the vegetation in an area with a continuous ELEVATION feature (measured in feet).

ID	STREAM	SLOPE	ELEVATION	VEGETATION
1	false	steep	3 900	chapparal
2	true	moderate	300	riparian
3	true	steep	1 500	riparian
4	false	steep	1 200	chapparal
5	false	flat	4 450	conifer
6	true	steep	5 000	conifer
7	true	steep	3 000	chapparal

Table 3: Dataset for predicting the vegetation in an area sorted by the continuous ELEVATION feature.

ID	STREAM	SLOPE	ELEVATION	VEGETATION
2	true	moderate	300	riparian
4	false	steep	1 200	chapparal
3	true	steep	1 500	riparian
7	true	steep	3 000	chapparal
1	false	steep	3 900	chapparal
5	false	flat	4 450	conifer
6	true	steep	5 000	conifer

Table 4: Partition sets (Part.), entropy, remainder (Rem.), and information gain (Info. Gain) for the candidate ELEVATION thresholds: ≥ 750, $\geq 1\,350$, $\geq 2\,250$ and $\geq 4\,175$.

Split by Threshold	Part.	Instances	Partition Entropy	Rem.	Info. Gain
≥ 750	$\mathcal{D}_1$	$\mathbf{d}_2$	0.0	1.2507	0.3060
	$\mathcal{D}_2$	$\mathbf{d}_4, \mathbf{d}_3, \mathbf{d}_7, \mathbf{d}_1, \mathbf{d}_5, \mathbf{d}_6$	1.4591		
$\geq 1\,350$	$\mathcal{D}_3$	$\mathbf{d}_2, \mathbf{d}_4$	1.0	1.3728	0.1839
	$\mathcal{D}_4$	$\mathbf{d}_3, \mathbf{d}_7, \mathbf{d}_1, \mathbf{d}_5, \mathbf{d}_6$	1.5219		
$\geq 2\,250$	$\mathcal{D}_5$	$\mathbf{d}_2, \mathbf{d}_4, \mathbf{d}_3$	0.9183	0.9650	0.5917
	$\mathcal{D}_6$	$\mathbf{d}_7, \mathbf{d}_1, \mathbf{d}_5, \mathbf{d}_6$	1.0		
$\geq 4\,175$	$\mathcal{D}_7$	$\mathbf{d}_2, \mathbf{d}_4, \mathbf{d}_3, \mathbf{d}_7, \mathbf{d}_1$	0.9710	0.6935	0.8631
	$\mathcal{D}_8$	$\mathbf{d}_5, \mathbf{d}_6$	0.0		

Feature Selection **Cont. Desc. Features** Cont. Targets Noise and Overfitting Ensembles Summary
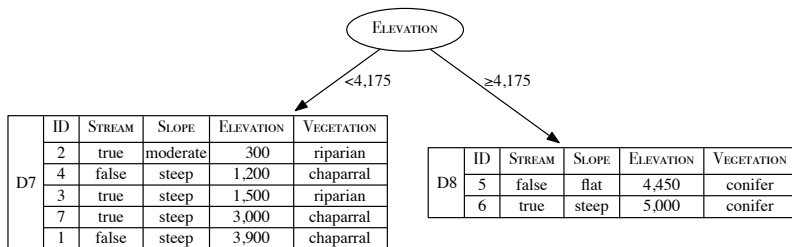
○○○○○○○○○○○○○○○○○○○○

Figure 2: The vegetation classification decision tree after the dataset has been split using ELEVATION $\geq$ 4 175.
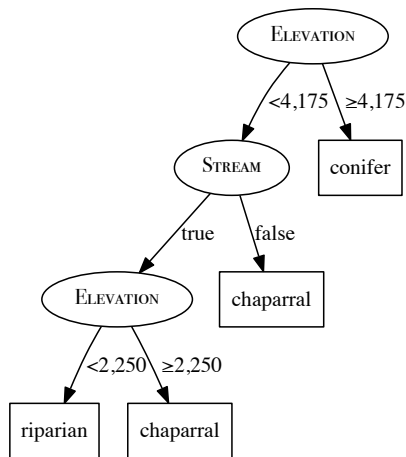
Figure 3: The decision tree that would be generated for the vegetation classification dataset listed in Table 3[17] using information gain.

Predicting Continuous Targets

Feature Selection   Cont. Desc. Features   **Cont. Targets**   Noise and Overfitting   Ensembles   Summary

○○○○○○○○○○○○○○○○○○○○○

- Regression trees are constructed so as to reduce the variance in the set of training examples at each of the leaf nodes in the tree
- We can do this by adapting the ID3 algorithm to use a measure of variance rather than a measure of classification impurity (entropy) when selecting the best attribute

- The impurity (variance) at a node can be calculated using the following equation:

$$var\left(t, \mathcal{D}\right) = \frac{\sum_{i=1}^{n} \left(t_i - \overline{t}\right)^2}{n - 1} \tag{3}$$

- We select the feature to split on at a node by selecting the feature that minimizes the weighted variance across the resulting partitions:

$$\mathbf{d}[best] = \underset{d \in \mathbf{d}}{\arg\min} \sum_{l \in levels(d)} \frac{|\mathcal{D}_{d=l}|}{|\mathcal{D}|} \times var(t, \mathcal{D}_{d=l}) \tag{4}$$
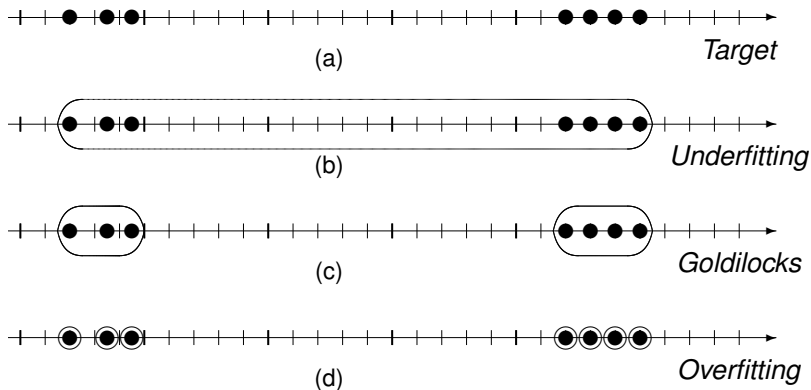
Figure 4: (a) A set of instances on a continuous number line; (b), (c), and (d) depict some of the potential groupings that could be applied to these instances.

Feature Selection   Cont. Desc. Features   **Cont. Targets**   Noise and Overfitting   Ensembles   Summary

○○○○○○○○○○○○○○○○○○○○

Table 5: A dataset listing the number of bike rentals per day.

ID	SEASON	WORK DAY	RENTALS	ID	SEASON	WORK DAY	RENTALS
1	winter	false	800	7	summer	false	3 000
2	winter	false	826	8	summer	true	5 800
3	winter	true	900	9	summer	true	6 200
4	spring	false	2 100	10	autumn	false	2 910
5	spring	true	4 740	11	autumn	false	2 880
6	spring	true	4 900	12	autumn	true	2 820

Table 6: The partitioning of the dataset in Table 5[25] based on SEASON and WORK DAY features and the computation of the weighted variance for each partitioning.

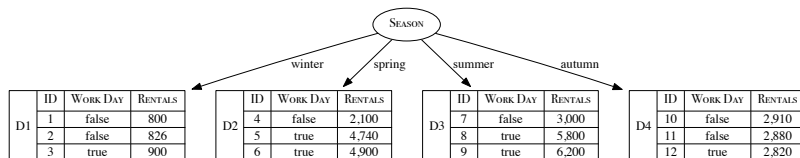| Split by Feature	Level	Part.	Instances	$\frac{|\mathcal{D}_{d=l}|}{|\mathcal{D}|}$	$var\,(t,\mathcal{D})$	Weighted Variance
SEASON	winter	$\mathcal{D}_1$	$\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3$	0.25	2 692	1 379 331$\frac{1}{3}$
	spring	$\mathcal{D}_2$	$\mathbf{d}_4, \mathbf{d}_5, \mathbf{d}_6$	0.25	2 472 533$\frac{1}{3}$	
	summer	$\mathcal{D}_3$	$\mathbf{d}_7, \mathbf{d}_8, \mathbf{d}_9$	0.25	3 040 000	
	autumn	$\mathcal{D}_4$	$\mathbf{d}_{10}, \mathbf{d}_{11}, \mathbf{d}_{12}$	0.25	2 100	
WORK DAY	true	$\mathcal{D}_5$	$\mathbf{d}_3, \mathbf{d}_5, \mathbf{d}_6, \mathbf{d}_8, \mathbf{d}_9, \mathbf{d}_{12}$	0.50	4 026 346$\frac{1}{3}$	2 551 813$\frac{1}{3}$
	false	$\mathcal{D}_6$	$\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_4, \mathbf{d}_7, \mathbf{d}_{10}, \mathbf{d}_{11}$	0.50	1 077 280	

Figure 5: The decision tree resulting from splitting the data in Table 5[25] using the feature SEASON.
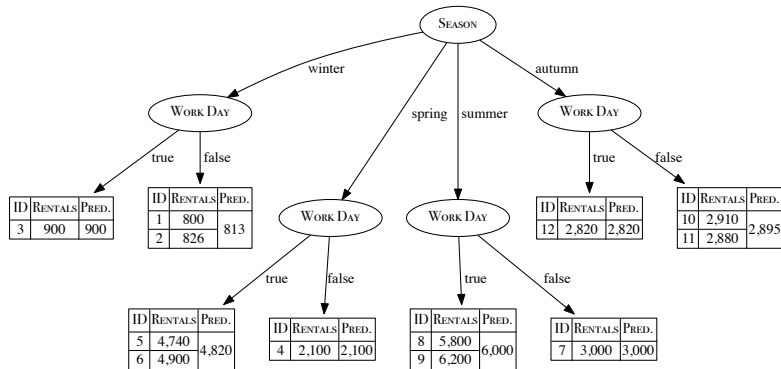
Figure 6: The final decision tree induced from the dataset in Table 5[25]. To illustrate how the tree generates predictions, this tree lists the instances that ended up at each leaf node and the prediction (PRED.) made by each leaf node.

Noisy Data, Overfitting and Tree Pruning

- In the case of a decision tree, over-fitting involves splitting the data on an irrelevant feature.

The likelihood of over-fitting occurring increases as a tree gets deeper because the resulting classifications are based on smaller and smaller subsets as the dataset is partitioned after each feature test in the path.

- **Pre-pruning**: stop the recursive partitioning early.
  Pre-pruning is also known as **forward pruning**.

Common Pre-pruning Approaches

1. **early stopping**

2. χ^2 **pruning**

- **Post-pruning**: allow the algorithm to grow the tree as
  much as it likes and then prune the tree of the branches
  that cause over-fitting.

Common Post-pruning Approach

- Using the validation set evaluate the prediction accuracy achieved by both the fully grown tree and the pruned copy of the tree. If the pruned copy of the tree performs no worse than the fully grown tree the node is a candidate for pruning.
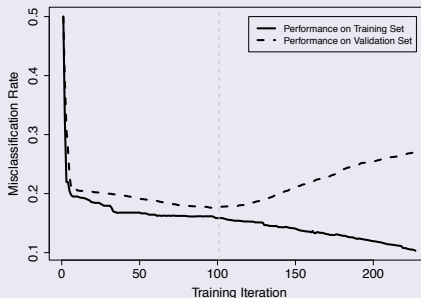
Feature Selection   Cont. Desc. Features   Cont. Targets   **Noise and Overfitting**   Ensembles   Summary

○○○○○○○○○○○○○○○○○○○○○

Table 7: An example validation set for the post-operative patient routing task.

ID	CORE-TEMP	STABLE-TEMP	GENDER	DECISION
1	high	true	male	gen
2	low	true	female	icu
3	high	false	female	icu
4	high	false	male	icu
5	low	false	female	icu
6	low	true	male	icu
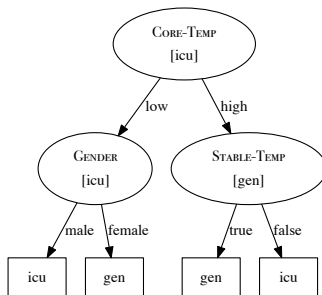
Figure 7: The decision tree for the post-operative patient routing task.

Feature Selection   Cont. Desc. Features   Cont. Targets   **Noise and Overfitting**   Ensembles   Summary
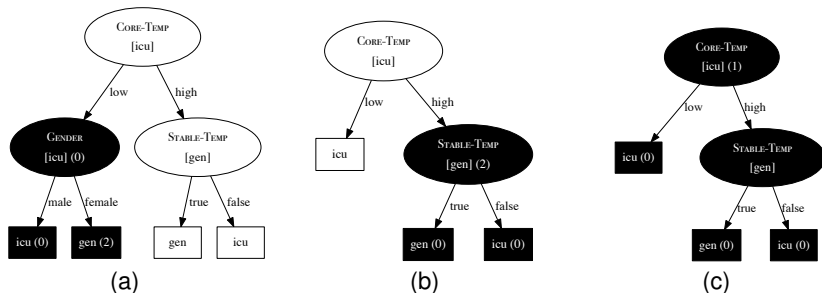
○○○○○○○○○○○○○○○○○○

Figure 8: The iterations of reduced error pruning for the decision tree in Figure 7[34] using the validation set in Table 7[33]. The subtree that is being considered for pruning in each iteration is highlighted in black. The prediction returned by each non-leaf node is listed in square brackets. The error rate for each node is given in round brackets.

Advantages of pruning:

- Smaller trees are easier to interpret
- Increased generalization accuracy when there is noise in the training data (**noise dampening**).

Model Ensembles

- Rather than creating a single model they generate a set of models and then make predictions by aggregating the outputs of these models.
- A prediction model that is composed of a set of models is called a **model ensemble**.
- In order for this approach to work the models that are in the ensemble must be different from each other.

- There are two standard approaches to creating ensembles:
  1. **bagging**.
  2. **boosting**

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

●○○○○○○○○○○○○○○○○○○

Bagging

- When we use **bagging** (or **bootstrap aggregating**) each model in the ensemble is trained on a random sample of the dataset known as **bootstrap samples**.
- Each random sample is the same size as the dataset and **sampling with replacement** is used.
- Consequently, every bootstrap sample will be missing some of the instances from the dataset so each bootstrap sample will be different and this means that models trained on different bootstrap samples will also be different

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

Bagging

- When bagging is used with decision trees each bootstrap sample only uses a randomly selected subset of the descriptive features in the dataset. This is known as **subspace sampling**.
- The combination of bagging, subspace sampling, and decision trees is known as a **random forest** model.
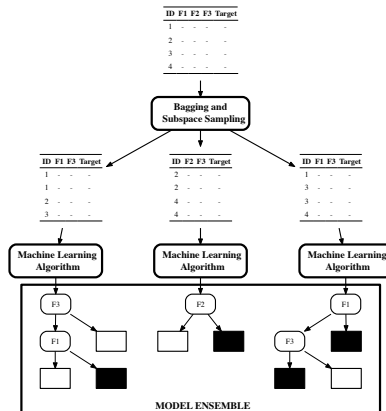
Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

Bagging

Figure 9: The process of creating a model ensemble using bagging and subspace sampling.

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

Boosting

- Boosting works by iteratively creating models and adding them to the ensemble.
- The iteration stops when a predefined number of models have been added.
- When we use **boosting** each new model added to the ensemble is biased to pay more attention to instances that previous models miss-classified.
- This is done by incrementally adapting the dataset used to train the models. To do this we use a **weighted dataset**

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

Boosting

Weighted Dataset

- Each instance has an associated weight $\mathbf{w}_i \geq 0$,
- Initially set to $\frac{1}{n}$ where n is the number of instances in the dataset.
- After each model is added to the ensemble it is tested on the training data and the weights of the instances the model gets correct are decreased and the weights of the instances the model gets incorrect are increased.
- These weights are used as a distribution over which the dataset is sampled to created a replicated training set, where the replication of an instance is proportional to its weight.

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

○○○○○●○○○○○○○○○○○○○○

Boosting

During each training iteration the algorithm:

1. Induces a model and calculates the total error, ϵ, by summing the weights of the training instances for which the predictions made by the model are incorrect.

2. Increases the weights for the instances misclassified using:

$$\mathbf{w}[i] \leftarrow \mathbf{w}[i] \times \left(\frac{1}{2 \times \epsilon} \right) \tag{5}$$

3. Decreases the weights for the instances correctly classified:

$$\mathbf{w}[i] \leftarrow \mathbf{w}[i] \times \left(\frac{1}{2 \times (1 - \epsilon)} \right) \tag{6}$$

4. Calculate a **confidence factor**, α, for the model such that α increases as ϵ decreases:

$$\alpha = \frac{1}{2} \times log_e \left(\frac{1 - \epsilon}{\epsilon} \right) \tag{7}$$

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

○○○○○○●○○○○○○○○○○○○

Boosting

- Once the set of models have been created the ensemble makes predictions using a weighted aggregate of the predictions made by the individual models.
- The weights used in this aggregation are simply the confidence factors associated with each model.

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

○○○○○○○●○○○○○○○○○○○

Boosting

Table 8: A simple bicycle demand predictions dataset and the workings of the first three iterations of training an ensemble model using boosting to predict RENTALS given TEMP.

			Iteration 0			Iteration 1			Iteration 2		
ID	TEMP	RENTALS	Dist.	Freq.	$\mathbb{M}_0(\mathbf{d})$	Dist.	Freq.	$\mathbb{M}_1(\mathbf{d})$	Dist.	Freq.	$\mathbb{M}_2(\mathbf{d})$
1	4	*Low*	0.100	2	*Low*	0.062	0	*High*	0.167	2	*Low*
2	5	*Low*	0.100	1	*Low*	0.062	1	*High*	0.167	1	*Low*
3	7	*Low*	0.100	0	*Low*	0.062	1	*High*	0.167	3	*Low*
4	12	*High*	0.100	1	*High*	0.062	2	*High*	0.038	0	*Low*
5	18	*High*	0.100	1	*High*	0.062	0	*High*	0.038	0	*Low*
6	23	*High*	0.100	1	*High*	0.062	0	*High*	0.038	0	*Low*
7	27	*High*	0.100	1	*High*	0.062	1	*High*	0.038	0	*Low*
8	28	*High*	0.100	1	*High*	0.062	1	*High*	0.038	1	*Low*
9	32	*Low*	0.100	2	*High*	0.250	3	*Low*	0.154	1	*Low*
10	35	*Low*	0.100	0	*High*	0.250	1	*Low*	0.154	2	*Low*

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary
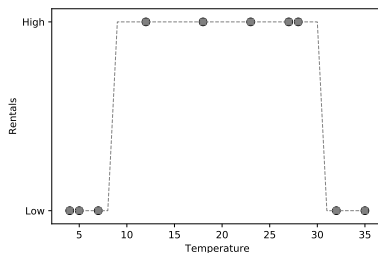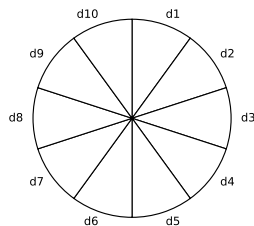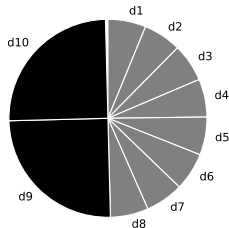○○○○○○○○○●○○○○○○○○○○
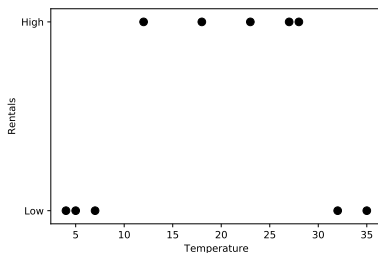
Boosting

(a) Training data

(b) The final ensemble model, $\mathbb{M}$

Figure 10: (a) A plot of the bike rental dataset from Table 8[47]. (b) An illustration of the final ensemble model trained using the boosting algorithm. (c)–(e) A representation of the changing weights used to generate sample datasets for the first iterations of the boosting process.

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary
○○○○○○○○○●○○○○○○○○

Boosting

(c) Distribution 0   (d) Distribution 1   (e) Distribution 2

Figure 11: (a) A plot of the bike rental dataset from Table 8[47]. (b) An illustration of the final ensemble model trained using the boosting algorithm. (c)–(e) A representation of the changing weights used to generate sample datasets for the first iterations of the boosting process.
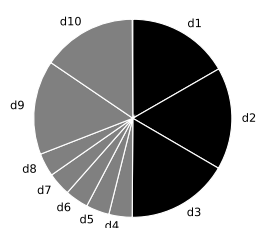
Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

Boosting

$$\mathbf{w}\,[1] \leftarrow 0.100 \times \left(\frac{1}{2 \times (1 - 0.200)} \right) \leftarrow 0.0625$$

$$\mathbf{w}\,[9] \leftarrow 0.100 \times \left(\frac{1}{2 \times 0.200} \right) \leftarrow 0.250$$

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary
○○○○○○○○○○○○●○○○○○○○

Gradient Boosting

$$\mathbb{M}_0(\mathbf{d}) = \frac{1}{n} \sum_i t_i \tag{8}$$

$$\mathbb{M}_1(\mathbf{d}) = \mathbb{M}_0(\mathbf{d}) + \mathbb{M}_{\Delta 1}(\mathbf{d}) \tag{9}$$

$$\mathbb{M}_i(\mathbf{d}) = \mathbb{M}_{i-1}(\mathbf{d}) + \mathbb{M}_{\Delta i}(\mathbf{d}) \tag{10}$$

Feature Selection Cont. Desc. Features Cont. Targets Noise and Overfitting **Ensembles** Summary

Gradient Boosting

$$\begin{aligned}
\mathbb{M}_4(\mathbf{d}) &= \mathbb{M}_3(\mathbf{d}) + \mathbb{M}_{\Delta 4}(\mathbf{d}) \\
&= (\mathbb{M}_2(\mathbf{d}) + \mathbb{M}_{\Delta 3}(\mathbf{d})) + \mathbb{M}_{\Delta 4}(\mathbf{d}) \\
&= ((\mathbb{M}_1 + \mathbb{M}_{\Delta 2}(\mathbf{d})) + \mathbb{M}_{\Delta 3}(\mathbf{d})) + \mathbb{M}_{\Delta 4}(\mathbf{d}) \\
&= (((\mathbb{M}_0(\mathbf{d}) + \mathbb{M}_{\Delta 1}(\mathbf{d})) + \mathbb{M}_{\Delta 2}(\mathbf{d})) + \mathbb{M}_{\Delta 3}(\mathbf{d})) + \mathbb{M}_{\Delta 4}(\mathbf{d}) \\
&= \mathbb{M}_0(\mathbf{d}) + \mathbb{M}_{\Delta 1}(\mathbf{d}) + \mathbb{M}_{\Delta 2}(\mathbf{d}) + \mathbb{M}_{\Delta 3}(\mathbf{d}) + \mathbb{M}_{\Delta 4}(\mathbf{d})
\end{aligned}$$

$$(11)$$

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

Gradient Boosting

Table 9: A simple bicycle demand predictions dataset and the workings of the first iterations of training a gradient boosting model.

ID	Temp	Rentals	$\mathbb{M}_0(\mathbf{d})$	$t - \mathbb{M}_0(\mathbf{d})$	$\mathbb{M}_{\Delta 1}(\mathbf{d})$	$\mathbb{M}_1(\mathbf{d})$	$t - \mathbb{M}_1(\mathbf{d})$	$\mathbb{M}_{\Delta 2}(\mathbf{d})$	$\mathbb{M}_2(\mathbf{d})$	$t - \mathbb{M}_2(\mathbf{d})$	$\mathbb{M}_{\Delta 3}(\mathbf{d})$	$\mathbb{M}_3(\mathbf{d})$
1	4	602	1 287.1	-685.1	-460.9	826.2	-224.2	-167.2	659.0	-57.0	-34.1	624.9
2	5	750	1 287.1	-537.1	-460.9	826.2	-76.2	-167.2	659.0	91.0	-34.1	624.9
3	7	913	1 287.1	-374.1	-460.9	826.2	86.8	71.6	897.8	15.2	-34.1	863.7
4	12	1229	1 287.1	-58.1	-460.9	826.2	402.8	71.6	897.8	331.2	-34.1	863.7
5	18	1827	1 287.1	539.9	691.4	1 978.5	-151.5	71.6	2 050.1	-223.1	-34.1	2 016.1
6	23	2246	1 287.1	958.9	691.4	1 978.5	267.5	71.6	2 050.1	195.9	136.4	2 186.5
7	27	2127	1 287.1	839.9	691.4	1 978.5	148.5	71.6	2 050.1	76.9	136.4	2 186.5
8	28	1714	1 287.1	426.9	691.4	1 978.5	-264.5	71.6	2 050.1	-336.1	-34.1	2 016.1
9	32	838	1 287.1	-449.1	-460.9	826.2	11.8	71.6	897.8	-59.8	-34.1	863.7
10	35	625	1 287.1	-662.1	-460.9	826.2	-201.2	-167.2	659.0	-34.0	-34.1	624.9

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

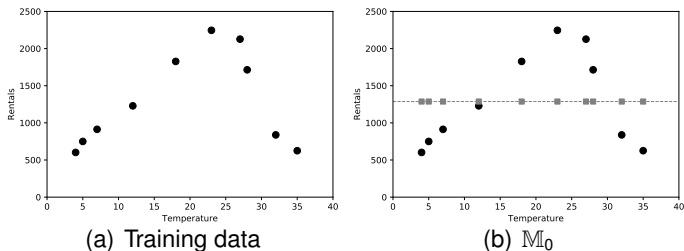Gradient Boosting

(a) Training data

(b) $\mathbb{M}_0$

Figure 12: (a) A plot of the bike rental dataset from Table 9[53]. (b)–(e) Visualizations of the prediction models trained in the early iterations of the gradient boosting process. (f) The final ensemble model trained after 20 iterations of gradient boosting.
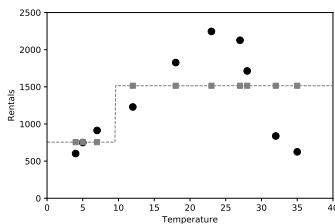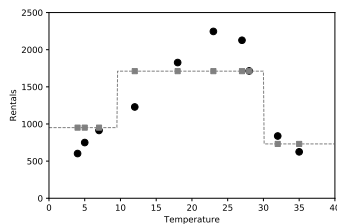
Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

○○○○○○○○○○○○○○○○●○○○

Gradient Boosting

(c) $\mathbb{M}_1$ (d) $\mathbb{M}_2$

Figure 13: (a) A plot of the bike rental dataset from Table 9[53]. (b)–(e) Visualizations of the prediction models trained in the early iterations of the gradient boosting process. (f) The final ensemble model trained after 20 iterations of gradient boosting.

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary
○○○○○○○○○○○○○○○○○○○○●○○

Gradient Boosting

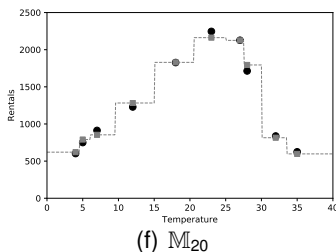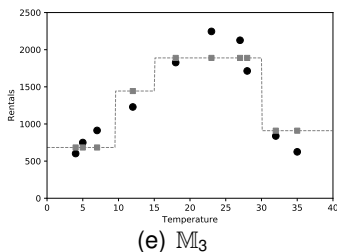(e) $\mathbb{M}_3$ (f) $\mathbb{M}_{20}$

Figure 14: (a) A plot of the bike rental dataset from Table 9[53]. (b)–(e) Visualizations of the prediction models trained in the early iterations of the gradient boosting process. (f) The final ensemble model trained after 20 iterations of gradient boosting.

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

Gradient Boosting

$$\mathbb{M}_i(\mathbf{d}) = \mathbb{M}_{i-1}(\mathbf{d}) + \alpha \times \mathbb{M}_{\Delta i}(\mathbf{d}) \qquad (12)$$

Feature Selection   Cont. Desc. Features   Cont. Targets   Noise and Overfitting   **Ensembles**   Summary

○○○○○○○○○○○○○○○○○○○●

Gradient Boosting

- Which approach should we use? Bagging is simpler to implement and parallelize than boosting and, so, may be better with respect to ease of use and training time.
- Empirical results indicate:
  - boosted decision tree ensembles were the best performing model of those tested for datasets containing up to 4,000 descriptive features.
  - random forest ensembles (based on bagging) performed better for datasets containing more that 4,000 features.

Summary

- The **decision tree** model makes predictions based on sequences of tests on the descriptive feature values of a query
- The **ID3** algorithm as a standard algorithm for inducing decision trees from a dataset.

Decision Trees: Advantages

- interpretable.
- handle both categorical and continuous descriptive features.
- has the ability to model the interactions between descriptive features (diminished if **pre-pruning** is employed)
- relatively, robust to the **curse of dimensionality**.
- relatively, robust to noise in the dataset if **pruning** is used.

Decision Tress: Potential Disadvantages

- trees become large when dealing with continuous features.
- decision trees are very expressive and sensitive to the dataset, as a result they can overfit the data if there are a lot of features (curse of dimensionality)
- eager learner (concept drift).

1 **Alternative Feature Selection Metrics**

2 **Handling Continuous Descriptive Features**

3 **Predicting Continuous Targets**

4 **Noisy Data, Overfitting and Tree Pruning**

5 **Model Ensembles**
- Bagging
- Boosting
- Gradient Boosting

6 **Summary**