Lecture 3: Decision Trees

Cognitive Systems II - Machine Learning
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Part I: Basic Approaches of Concept Learning

ID3, Information Gain, Overfitting, Pruning
**Decision Tree Representation**

- classification of instances by sorting them down the tree from the root to some leaf node
  - **node** $\approx$ test of some attribute
  - **branch** $\approx$ one of the possible values for the attribute

- decision trees represent a **disjunction of conjunctions of constraints** on the attribute values of instances
  - i.e., $(\ldots \land \ldots \land \ldots) \lor (\ldots \land \ldots \land \ldots) \lor \ldots$

- equivalent to a set of if-then-rules
  - each branch represents one if-then-rule
    - **if-part**: conjunctions of attribute tests on the nodes
    - **then-part**: classification of the branch
This decision tree is equivalent to:

\[
\text{if } (\text{Outlook} = \text{Sunny}) \land (\text{Humidity} = \text{Normal}) \text{ then Yes;} \\
\text{if } (\text{Outlook} = \text{Overcast}) \text{ then Yes;} \\
\text{if } (\text{Outlook} = \text{Rain}) \land (\text{Wind} = \text{Weak}) \text{ then Yes;} \\
\]
Appropriate Problems

- Instances are represented by attribute-value pairs, e.g. (Temperature, Hot)
- Target function has discrete output values, e.g. yes or no (concept/classification learning)
- Disjunctive descriptions may be required
- Training data may contain errors
- Training data may contain missing attribute values

⇒ last three points make Decision Tree Learning more attractive than CANDIDATE-ELIMINATION
ID3

- learns decision trees by constructing them **top-down**
- employs a **greedy search algorithm without backtracking** through the space of all possible decision trees
  - finds a short tree (wrt path length) but not necessarily the best decision tree

**key idea:**
- selection of the next attribute according to a statistical measure
- all examples are considered at the same time (simultaneous covering)
- recursive application with reduction of selectable attributes until each training example can be classified unambiguously
ID3 Algorithm for Concept Learning

ID3(Examples, Target_attribute, Attributes)

- Create a Root for the tree
- If all examples are positive, Return single-node tree Root, with label = +
- If all examples are negative, Return single-node tree Root, with label = −
- If Attributes is empty, Return single-node tree Root, with label = most common value of Target_attribute in Examples
- otherwise, Begin
  - \( A \leftarrow \) attribute in Attributes that best classifies Examples
  - decision attribute for Root \( \leftarrow A \)
  - For each possible value \( v_i \) of \( A \)
    - Add new branch below Root with \( A = v_i \)
    - Let \( Examples_{v_i} \) be the subset of Examples with \( v_i \) for \( A \)
    - If \( Examples_{v_i} \) is empty
      - Then add a leaf node with label = most common value of Target_attribute in Examples
    - Else add ID3(\( Examples_{v_i} \), Target_Attribute, Attributes − \{A\})

- Return Root
The best classifier

**central choice:** Which attribute classifies the examples best?

**ID3 uses the information gain**

- statistical measure that indicates how well a given attribute separates the training examples according to their target classification

\[
Gain(S, A) \equiv Entropy(S) - \sum_{v \in \text{values}(A)} \frac{|S_v|}{|S|} \cdot Entropy(S_v)
\]

- interpretation:
  - denotes the reduction in entropy caused by partitioning \( S \) according to \( A \)
  - alternative: number of saved yes/no questions (i.e., bits)

\( \Rightarrow \) attribute with \( \max_A Gain(S, A) \) is selected!
Entropy

- statistical measure from information theory that characterizes (im-)purity of an arbitrary collection of examples $S$

- for binary classification: $H(S) \equiv -p_\oplus \log_2 p_\oplus - p_\ominus \log_2 p_\ominus$

- for n-ary classification: $H(S) \equiv \sum_{i=1}^{n} -p_i \log_2 p_i$

- interpretation:
  - specification of the minimum number of bits of information needed to encode the classification of an arbitrary member of $S$
  - alternative: number of yes/no questions
Entropy

- **minimum** of $H(S)$
  - for minimal impurity $\rightarrow$ point distribution
  - $H(S) = 0$

- **maximum** of $H(S)$
  - for maximal impurity $\rightarrow$ uniform distribution
  - for binary classification: $H(S) = 1$
  - for n-ary classification: $H(S) = \log_2 n$
### Illustrative Example

**Example Days**

<table>
<thead>
<tr>
<th>Day</th>
<th>Outlook</th>
<th>Temp.</th>
<th>Humidity</th>
<th>Wind</th>
<th>PlayTennis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Sunny</td>
<td>Hot</td>
<td>High</td>
<td>Weak</td>
<td>No</td>
</tr>
<tr>
<td>D2</td>
<td>Sunny</td>
<td>Hot</td>
<td>High</td>
<td>Strong</td>
<td>No</td>
</tr>
<tr>
<td>D3</td>
<td>Overcast</td>
<td>Hot</td>
<td>High</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D4</td>
<td>Rain</td>
<td>Mild</td>
<td>High</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D5</td>
<td>Rain</td>
<td>Cool</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D6</td>
<td>Rain</td>
<td>Cool</td>
<td>Normal</td>
<td>Strong</td>
<td>No</td>
</tr>
<tr>
<td>D7</td>
<td>Overcast</td>
<td>Cool</td>
<td>Normal</td>
<td>Strong</td>
<td>Yes</td>
</tr>
<tr>
<td>D8</td>
<td>Sunny</td>
<td>Mild</td>
<td>High</td>
<td>Weak</td>
<td>No</td>
</tr>
<tr>
<td>D9</td>
<td>Sunny</td>
<td>Cool</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D10</td>
<td>Rain</td>
<td>Mild</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D11</td>
<td>Sunny</td>
<td>Mild</td>
<td>Normal</td>
<td>Strong</td>
<td>Yes</td>
</tr>
<tr>
<td>D12</td>
<td>Overcast</td>
<td>Mild</td>
<td>High</td>
<td>Strong</td>
<td>Yes</td>
</tr>
<tr>
<td>D13</td>
<td>Overcast</td>
<td>Hot</td>
<td>Normal</td>
<td>Weak</td>
<td>Yes</td>
</tr>
<tr>
<td>D14</td>
<td>Rain</td>
<td>Mild</td>
<td>High</td>
<td>Strong</td>
<td>No</td>
</tr>
</tbody>
</table>
Illustrative Example

- entropy of $S$

$$S = \{D1, ..., D14\} = [9+, 5-]$$

$$H(S) = -\frac{9}{14} \cdot \log_2 \frac{9}{14} - \frac{5}{14} \cdot \log_2 \frac{5}{14} = 0.940$$

- information gain (e.g. $Wind$)

$$S_{Weak} = \{D1, D3, D4, D5, D8, D9, D10, D13\} = [6+, 2-]$$

$$S_{Strong} = \{D2, D6, D7, D11, D12, D4\} = [3+, 3-]$$

$$Gain(S, Wind) = H(S) - \sum_{v \in Wind} \frac{|S_v|}{|S|} \cdot H(S_v)$$

$$= H(S) - \frac{8}{14} \cdot H(S_{Weak}) - \frac{6}{14} \cdot H(S_{Strong})$$

$$= 0.940 - \frac{8}{14} \cdot 0.811 - \frac{6}{14} \cdot 1.000$$

$$= 0.048$$
Illustrative Example

Which attribute is the best classifier?

Gain (S, Humidity)
= .940 - (7/14).985 - (7/14).592
= .151

Gain (S, Wind)
= .940 - (8/14).811 - (6/14)1.0
= .048
Illustrative Example

- informations gains for the four attributes:
  
  \[
  \text{Gain}(S, \text{Outlook}) = 0.246 \\
  \text{Gain}(S, \text{Humidity}) = 0.151 \\
  \text{Gain}(S, \text{Wind}) = 0.048 \\
  \text{Gain}(S, \text{Temperature}) = 0.029
  \]

  ⇒ Outlook is selected as best classifier and is therefore Root of the tree

  ⇒ now branches are created below the root for each possible value

  - because every example for which Outlook = Overcast is positive, this node becomes a leaf node with the classification Yes
  - the other descendants are still ambiguous (\(H(S) \neq 0\))
  - hence, the decision tree has to be further elaborated below these nodes
Illustrative Example

Which attribute should be tested here?

\[ S_{\text{Sunny}} = \{D1, D2, D8, D9, D11\} \]

\[
Gain(S_{\text{Sunny}}, \text{Humidity}) = .970 - \frac{3}{5} \cdot 0.0 - \frac{2}{5} \cdot 0.0 = .970
\]

\[
Gain(S_{\text{Sunny}}, \text{Temperature}) = .970 - \frac{2}{5} \cdot 0.0 - \frac{2}{5} \cdot 1.0 - \frac{1}{5} \cdot 0.0 = .570
\]

\[
Gain(S_{\text{Sunny}}, \text{Wind}) = .970 - \frac{2}{5} \cdot 1.0 - \frac{3}{5} \cdot .918 = .019
\]
Illustrative Example

Resulting decision tree

- **Outlook**
  - Sunny
  - Humidity
    - High
      - No
    - Normal
      - Yes
  - Overcast
    - Yes
  - Rain
    - Wind
      - Strong
      - No
      - Weak
      - Yes
Hypothesis Space Search

\[ H \approx \text{complete space of finite discrete functions, relative to the available attributes (i.e. all possible decision trees)} \]

**capabilties and limitations:**
- returns just one single consistent hypothesis
- performs greedy search (i.e., \( \max_A Gain(S, A) \))
- susceptible to the usual risks of hill-climbing without backtracking
- uses all training examples at each step \( \Rightarrow \) simultaneous covering
Inductive Bias

as mentioned above, ID3 searches

*complete* space of possible hypotheses (wrt instance space),
but not *completely* ⇒ Preference Bias

**Inductive bias**: Shorter trees are preferred to longer trees. Trees that place high information gain attributes close to the root are also preferred.

Why prefer shorter hypotheses?

- **Occam’s Razor**: Prefer the simplest hypothesis that fits the data!
  (aka W. Ockham)
- see Minimum Description Length Principle (Bayesian Learning)
- e.g., if there are two decision trees, one with 500 nodes and another with 5 nodes, the second one should be preferred
  ⇒ better chance to avoid overfitting
Given a hypothesis space $H$, a hypothesis $h \in H$ is said to **overfit** the training data if there exists some alternative hypothesis $h' \in H$, such that $h$ has smaller error than $h'$ over the training data, but $h'$ has smaller error than $h$ over the entire distribution of instances.
Overfitting

- reasons for overfitting:
  - noise in the data
  - number of training examples is too small to produce a representative sample of the target function

- how to avoid overfitting:
  - stop the tree growing earlier, before it reaches the point where it perfectly classifies the training data
  - allow overfitting and then post-prune the tree (more successful in practice!)

- how to determine the perfect tree size:
  - separate validation set to evaluate utility of post-pruning
  - apply statistical test to estimate whether expanding (or pruning) produces an improvement
Reduced Error Pruning

- each of the decision nodes is considered to be a candidate for pruning

- **pruning** a decision node consists of removing the subtree rooted at the node, making it a leaf node and assigning the most common classification of the training examples affiliated with that node

- nodes are removed only if the resulting tree performs **not worse** than the original tree over the validation set

- pruning starts with the node whose removal most increases accuracy and continues until further pruning is harmful
Reduced Error Pruning

Effect of reduced error pruning:

Any node added to coincidental regularities in the training set is likely to be pruned.
Rule Post-Pruning

rule post-pruning involves the following steps:

1. Infer the decision tree from the training set (Overfitting allowed!)
2. Convert the tree into a set of rules
3. Prune each rule by removing any preconditions that result in improving its estimated accuracy
4. Sort the pruned rules by their estimated accuracy

one method to estimate rule accuracy is to use a separate validation set

pruning rules is more precise than pruning the tree itself
Alternative measures

natural bias in information gain favors attributes with many values over those with few values

e.g. attribute *Date*

- very large number of values (e.g. March 21, 2005)
- inserted in the above example, it would have the highest information gain, because it perfectly separates the training data
- but the classification of unseen examples would be impossible

alternative measure: *GainRatio*

\[
\text{GainRatio}(S, A) = \frac{\text{Gain}(S, A)}{\text{SplitInformation}(S, A)}
\]

\[
\text{SplitInformation}(S, A) = -\sum_{i=1}^{n} \frac{|S_i|}{|S|} \log_2 \frac{|S_i|}{|S|}
\]

*SplitInformation*(\(S, A\)) is sensitive to how broadly and uniformly \(A\) splits \(S\) (entropy of \(S\) with respect to the values of \(A\))

\( \Rightarrow \) *GainRatio* penalizes attributes such as *Date*
Real-Valued Attributes

- Decision tree learning with real valued attributes is possible
- Discretization of data by split in two ranges (ID3) estimating number of best discriminating ranges (CAL5)
- One attribute must be allowed to occur more than one time on a path in the decision tree!
Determining the Generalization Error

- Simple method: Randomly select part of the data from the training set for a test set
- Unbiased estimate of error because hypothesis is chosen independently of test cases
- But: the estimated error may still vary from the true error!
- Estimate the confidence interval in which the true error lies with a certain probability (see Mitchell, chap. 5)
Bagging and Boosting

Bagging (bootstrap aggregation, Breimann, 1996):
- Reduce variance in classification
- Calculate $M$ classifiers over different bootstrap samples
- Prediction by majority vote

Boosting (Freund & Schapire, 1996)
- Reduce variance and bias in classification
- Additionally introduce weights for each classifier which are iteratively adjusted (due to classification failure/success)

see diploma thesis of Jörg Mennicke: Classifier Learning for Imbalanced Data with Varying Misclassification Costs - A Comparison of kNN, SVM, and Decision Tree Learning (2006)
For many learning algorithms, it is useful to provide an additional validation set (e.g. for parameter fitting)

**k-fold cross validation:**

- partition training set with $m$ examples into $k$ disjoint subsets of size $\frac{m}{k}$
- run $k$ times with a different subset as validation set each time (using the combined other subsets as training set)
- Calculate the mean of your estimates over the $k$ runs
- Last run with complete training set and parameters fixed to the estimates
The Problem of Imbalanced Data

- In realistic settings occurrence of different classes might be imbalanced (e.g. cancer screening, quality control)
- Undersampling (remove examples for the over-represented class), oversampling (clone data for the under-represented class)
- Estimate is worse for the class which occurs more seldomly, this might be the class with higher misclassification costs (e.g. decide no cancer if true class is cancer)
- Instead of over-/, undersampling, introduce different costs for misclassifications and calculate weighted error measure!
- see e.g.: Tom Hecker and Jörg Mennicke, Diagnosing Cancerous Abnormalities with Decision Tree Learning, Student Project in cooperation with Fraunhofer IIS, 2005.
Compare Learners

- Which learner obtains better results in some domain?
- Compare whether generalization error of one is significantly lower than of the other
- Use similar procedure to $k$-fold cross-validation to obtain data for inference statistical comparison (see Mitchell, chap. 5)
practical and intuitively understandable method for concept learning

able to learn disjunctive, discrete-valued concepts

noise in the data is allowed

**ID3** is a simultaneous covering algorithm based on information gain that performs a greedy top-down search through the space of possible decision trees

**Inductive Bias**: Short trees are preferred (Ockham’s Razor)

overfitting is an important issue and can be reduced by pruning