Chapters 8-9. Classification

- Classification: Basic Concepts
- Decision Tree Induction
- Model Evaluation/Learning Algorithm Evaluation
- Rule-Based Classification
- Bayes Classification Methods
- Bayesian Belief Networks (ch9)
- Techniques to Improve Classification
- Lazy Learners (ch9)
- Other known methods: SVM, ANN (ch9)
Supervised vs. Unsupervised Learning

- **Supervised learning (classification)**
  - Supervision: training data are labeled indicating classes
  - New instances are classified based on training set

- **Unsupervised learning (clustering)**
  - Class labels are unknown
  - Given a set of objects, establish the existence of classes or clusters in the data
Classification
- predicts categorical class labels

Numeric prediction
- models continuous-valued functions, i.e., predicts unknown or missing values

Typical applications
- Credit/loan approval
- Medical diagnosis
- Fraud detection
- Web page categorization
Model construction: describing a set of predetermined classes

- Each tuple/sample is assumed to belong to a predefined class, as indicated by the class label attribute
- The set of tuples used for model construction is training set
- The model is represented as classification rules, decision trees, or mathematical formulae

Model usage: for classifying future or unknown instances

- Estimate accuracy of the model
  - Use an independent (of training set) testing set, compare predicted class labels with true class labels
  - Compute accuracy (percentage of correctly classified instances)
- If the accuracy is acceptable, use the model to classify new data
Process 1: Model Construction

<table>
<thead>
<tr>
<th>NAME</th>
<th>RANK</th>
<th>YEARS</th>
<th>TENURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mike</td>
<td>Assistant Prof</td>
<td>3</td>
<td>no</td>
</tr>
<tr>
<td>Mary</td>
<td>Assistant Prof</td>
<td>7</td>
<td>yes</td>
</tr>
<tr>
<td>Bill</td>
<td>Professor</td>
<td>2</td>
<td>yes</td>
</tr>
<tr>
<td>Jim</td>
<td>Associate Prof</td>
<td>7</td>
<td>yes</td>
</tr>
<tr>
<td>Dave</td>
<td>Assistant Prof</td>
<td>6</td>
<td>no</td>
</tr>
<tr>
<td>Anne</td>
<td>Associate Prof</td>
<td>3</td>
<td>no</td>
</tr>
</tbody>
</table>

IF rank = ‘professor’ OR years > 6
THEN tenured = ‘yes’
Process 2: Using the Model in Prediction

<table>
<thead>
<tr>
<th>NAME</th>
<th>RANK</th>
<th>YEARS</th>
<th>TENURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tom</td>
<td>Assistant Prof</td>
<td>2</td>
<td>no</td>
</tr>
<tr>
<td>Merlisa</td>
<td>Associate Prof</td>
<td>7</td>
<td>no</td>
</tr>
<tr>
<td>George</td>
<td>Professor</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>Joseph</td>
<td>Assistant Prof</td>
<td>7</td>
<td>yes</td>
</tr>
</tbody>
</table>

Unseen Data

(Jeff, Professor, 4)

Tenured? Yes
Issues: Data Preparation

- Data cleaning
  - Preprocess data in order to reduce noise and handle missing values
- Relevance analysis (feature selection)
  - Remove the irrelevant or redundant attributes
- Data transformation
  - Generalize and/or normalize data
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Decision Tree Induction: An Example

- Training data set: Buys_computer
- Resulting tree:
Algorithm for Decision Tree Induction

- Basic algorithm (a greedy algorithm)
  - Tree is constructed in a top-down (from general to specific) recursive divide-and-conquer manner
  - At start, all the training examples are at the root
  - Attributes are categorical (if continuous-valued, discretization in advance)
  - Examples are partitioned recursively based on selected attributes
  - Attributes are selected based on heuristic or statistical measure (e.g., information gain)

- When to stop
  - All example for a given node belong to the same class (pure), or
  - No remaining attributes to select from, or
    - majority voting to determine class label for the node
  - No examples left
Random Tree Induction

Let $a$ be the number of attributes. Let $v$ be the maximum number of values any attribute can take

- Upper bound on the number of trees?
- Lower bound on the number of trees?

- Random tree induction
  - Randomly choose an attribute for split
  - Same stopping criteria

- The design of decision trees has been largely influenced by the preference for simplicity.
Occam’s Razor

- Occam’s Razor: rule of parsimony, principle of economy
  - plurality should not be assumed without necessity
  - meaning, one should not increase, beyond what is necessary, the number of entities required to explain anything

- Argument: the simplicity of nature and rarity of simple theories can be used to justify Occam's Razer.
  - First, nature exhibits regularity and natural phenomena are more often simple than complex. At least, the phenomena humans choose to study tend to have simple explanations.
  - Second, there are far fewer simple hypotheses than complex ones, so that there is only a small chance that any simple hypothesis that is wildly incorrect will be consistent with all observations.

- Occam's two razors: The sharp and the blunt (KDD’98)
  - Pedro Domingos
Attribute Selection Measure: Information Gain (ID3/C4.5)

- How to obtain smallest (shortest) tree?
- Careful design on selection of attribute
- Quinlan pioneered using entropy in his ID3 algorithm
- Entropy: in information theory, also called expected information, is a measure of uncertainly
- Intuition: chaos, molecular disorder, temperature, thermodynamic system, universe
  - High entropy = high disorder
Attribute Selection Measure: Information Gain (ID3/C4.5)

- Select the attribute with the highest information gain
- Let $p_i$ be the probability that an arbitrary tuple in $D$ belongs to class $C_i$, estimated by $|C_{i,D}|/|D|$
- **Expected information** (entropy) needed to classify a tuple in $D$:
  \[
  \text{Info}(D) = - \sum_{i=1}^{m} p_i \log_2 (p_i)
  \]
  - entropy: measure of uncertainty. Larger entropy $\rightarrow$ larger uncertainty
- **Information** needed to classify $D$ (aggregated entropy after using $A$ to split $D$ into $v$ partitions):
  \[
  \text{Info}_A(D) = \sum_{j=1}^{v} \frac{|D_j|}{|D|} \times \text{Info}(D_j)
  \]
- **Information gained** (entropy dropped) by branching on attribute $A$
  \[
  \text{Gain}(A) = \text{Info}(D) - \text{Info}_A(D)
  \]
Attribute Selection: Information Gain

- Class P: buys_computer = “yes”
- Class N: buys_computer = “no”

\[
\text{Info}(D) = I(9,5) = -\frac{9}{14} \log_2 \left( \frac{9}{14} \right) - \frac{5}{14} \log_2 \left( \frac{5}{14} \right) = 0.940
\]

<table>
<thead>
<tr>
<th>age</th>
<th>( p_i )</th>
<th>( n_i )</th>
<th>( l(p_i, n_i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;=30</td>
<td>2</td>
<td>3</td>
<td>0.971</td>
</tr>
<tr>
<td>31…40</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&gt;40</td>
<td>3</td>
<td>2</td>
<td>0.971</td>
</tr>
</tbody>
</table>

\[
\text{Info}_{age}(D) = \frac{5}{14} I(2,3) + \frac{4}{14} I(4,0)
\]

\[
+ \frac{5}{14} I(3,2) = 0.694
\]

\[
\frac{5}{14} I(2,3) \text{ means “age <=30” has 5 out of 14 samples, with 2 yes’es and 3 no’s. Hence}
\]

\[
\text{Gain}(age) = \text{Info}(D) - \text{Info}_{age}(D) = 0.246
\]

Similarly,

\[
\text{Gain}(income) = 0.029
\]

\[
\text{Gain}(student) = 0.151
\]

\[
\text{Gain}(credit \_ rating) = 0.048
\]
Let attribute A be a continuous-valued attribute

Must determine the *best split point* for A

- Sort the value A in increasing order
- Typically, the midpoint between each pair of adjacent values is considered as a possible *split point*
  - \((a_i + a_{i+1})/2\) is the midpoint between the values of \(a_i\) and \(a_{i+1}\)
- The point with the *minimum expected information requirement* for A is selected as the split-point for A

Split:

- D1 is the set of tuples in D satisfying \(A \leq\) split-point, and D2 is the set of tuples in D satisfying \(A >\) split-point
Gain Ratio for Attribute Selection (C4.5)

- Information gain is biased towards attributes with a large number of values.
- C4.5 (a successor of ID3) uses gain ratio to overcome the problem (normalization to information gain).

\[
SplitInfo_A(D) = -\sum_{j=1}^{v} \frac{|D_j|}{|D|} \times \log_2\left( \frac{|D_j|}{|D|} \right)
\]

- GainRatio(A) = Gain(A) / SplitInfo(A)

\[
SplitInfo_{\text{income}}(D) = -\frac{4}{14} \times \log_2\left( \frac{4}{14} \right) - \frac{6}{14} \times \log_2\left( \frac{6}{14} \right) - \frac{4}{14} \times \log_2\left( \frac{4}{14} \right) = 1.557.
\]

\[
gain\_ratio(\text{income}) = 0.029/1.557 = 0.019.
\]
- The attribute with the largest gain ratio will be selected.
**Gini Index (CART, IBM IntelligentMiner)**

- If a data set $D$ contains examples from $n$ classes, gini index, $gini(D)$ is defined as

  $$gini(D) = 1 - \sum_{j=1}^{n} p_j^2$$

  where $p_j$ is the relative frequency of class $j$ in $D$

- If a data set $D$ is split on $A$ into two subsets $D_1$ and $D_2$, the gini index $gini(D)$ is defined as

  $$gini_A(D) = \frac{|D_1|}{|D|} gini(D_1) + \frac{|D_2|}{|D|} gini(D_2)$$

- Reduction in Impurity:

  $$\Delta gini(A) = gini(D) - gini_A(D)$$

- The attribute provides the smallest $gini_{split}(D)$ (or the largest reduction in impurity) is chosen to split the node (*need to enumerate all the possible splitting points for each attribute*)
Computation of Gini Index

- Ex. D has 9 tuples in buys_computer = “yes” and 5 in “no”
  \[ gini(D) = 1 - \left( \frac{9}{14} \right)^2 - \left( \frac{5}{14} \right)^2 = 0.459 \]

- Suppose the attribute income partitions D into 10 in D₁: \{low, medium\} and 4 in D₂
  \[ gini_{income \in \{low, medium\}}(D) = \left( \frac{10}{14} \right) Gini(D₁) + \left( \frac{4}{14} \right) Gini(D₂) \]
  \[ = \frac{10}{14} \left( 1 - \left( \frac{7}{10} \right)^2 - \left( \frac{3}{10} \right)^2 \right) + \frac{4}{14} \left( 1 - \left( \frac{2}{4} \right)^2 - \left( \frac{2}{4} \right)^2 \right) \]
  \[ = 0.443 \]
  \[ = Gini_{income \in \{high\}}(D). \]

  \( Gini_{\{low,high\}} \) is 0.458; \( Gini_{\{medium,high\}} \) is 0.450. Thus, split on the \{low,medium\} (and \{high\}) since it has the lowest Gini index

- All attributes are assumed continuous-valued
- May need other tools, e.g., clustering, to get the possible split values
- Can be modified for categorical attributes
Comparing Attribute Selection Measures

- The three measures, in general, return good results but
  - **Information gain:**
    - biased towards multivalued attributes
  - **Gain ratio:**
    - tends to prefer unbalanced splits in which one partition is much smaller than the others
  - **Gini index:**
    - biased to multivalued attributes
    - has difficulty when # of classes is large
    - tends to favor tests that result in equal-sized partitions and purity in both partitions
Other Attribute Selection Measures

- **CHAID**: a popular decision tree algorithm, measure based on $\chi^2$ test for independence
- **C-SEP**: performs better than info. gain and gini index in certain cases
- **G-statistic**: has a close approximation to $\chi^2$ distribution
- **MDL (Minimal Description Length) principle** (i.e., the simplest solution is preferred):
  - The best tree as the one that requires the fewest # of bits to both (1) encode the tree, and (2) encode the exceptions to the tree
- Multivariate splits (partition based on multiple variable combinations)
  - **CART**: finds multivariate splits based on a linear comb. of attrs.
- Which attribute selection measure is the best?
  - Most give good results, none is significantly superior than others
Overfitting and Tree Pruning

- **Overfitting**: An induced tree may overfit the training data
  - Too many branches, some may reflect anomalies due to noise or outliers
  - Poor accuracy for unseen samples
  - Blue: training error, red: generalization error

- Two approaches to avoid overfitting
  - **Prepruning**: Halt tree construction early—do not split a node if this would result in the goodness measure falling below a threshold
    - Difficult to choose an appropriate threshold
  - **Postpruning**: Remove branches from a “fully grown” tree—get a sequence of progressively pruned trees
    - Use a set of data (validation set) different from the training data to decide which is the “best pruned tree”
Enhancements to Basic Decision Tree Induction

- Allow for **continuous-valued attributes**
  - Dynamically define new discrete-valued attributes that partition the continuous attribute value into a discrete set of intervals
- Handle **missing attribute values**
  - Assign the most common value of the attribute
  - Assign probability to each of the possible values
- **Attribute construction**
  - Create new attributes based on existing ones that are sparsely represented
  - This reduces fragmentation, repetition, and replication
Classification in Large Databases

- Classification—a classical problem extensively studied by statisticians and machine learning researchers
- Scalability: Classifying data sets with millions of examples and hundreds of attributes with reasonable speed
- Why is decision tree induction popular?
  - relatively faster learning speed (than other classification methods)
  - convertible to simple and easy to understand classification rules
  - can use SQL queries for accessing databases
  - comparable classification accuracy with other methods
- RainForest (VLDB’ 98 — Gehrke, Ramakrishnan & Ganti)
  - Builds an AVC-list (attribute, value, class label)
Scalability Framework for RainForest

- Separates the scalability aspects from the criteria that determine the quality of the tree
- Builds an AVC-list: **AVC (Attribute, Value, Class_label)**
- **AVC-set** (of an attribute $X$)
  - Projection of training dataset onto the attribute $X$ and class label where counts of individual class label are aggregated
- **AVC-group** (of a node $n$)
  - Set of AVC-sets of all predictor attributes at the node $n$
## Rainforest: Training Set and Its AVC Sets

### Training Examples

<table>
<thead>
<tr>
<th>age</th>
<th>income</th>
<th>student</th>
<th>credit_rating</th>
<th>Buy_Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;=30</td>
<td>high</td>
<td>no</td>
<td>fair</td>
<td>no</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>high</td>
<td>no</td>
<td>excellent</td>
<td>no</td>
</tr>
<tr>
<td>31…40</td>
<td>high</td>
<td>no</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>medium</td>
<td>no</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>low</td>
<td>yes</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>low</td>
<td>yes</td>
<td>excellent</td>
<td>no</td>
</tr>
<tr>
<td>31…40</td>
<td>low</td>
<td>yes</td>
<td>excellent</td>
<td>yes</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>medium</td>
<td>no</td>
<td>fair</td>
<td>no</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>medium</td>
<td>yes</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>medium</td>
<td>yes</td>
<td>excellent</td>
<td>yes</td>
</tr>
<tr>
<td>31…40</td>
<td>medium</td>
<td>no</td>
<td>excellent</td>
<td>yes</td>
</tr>
<tr>
<td>31…40</td>
<td>high</td>
<td>yes</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>medium</td>
<td>no</td>
<td>excellent</td>
<td>no</td>
</tr>
</tbody>
</table>

### AVC-Set on Age

<table>
<thead>
<tr>
<th>Age</th>
<th>Buy_Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;=30</td>
<td>yes</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>no</td>
</tr>
<tr>
<td>31…40</td>
<td>yes</td>
</tr>
<tr>
<td>31…40</td>
<td>no</td>
</tr>
<tr>
<td>&gt;40</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>no</td>
</tr>
</tbody>
</table>

### AVC-Set on Income

<table>
<thead>
<tr>
<th>income</th>
<th>Buy_Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>high</td>
<td>2</td>
</tr>
<tr>
<td>medium</td>
<td>4</td>
</tr>
<tr>
<td>low</td>
<td>3</td>
</tr>
</tbody>
</table>

### AVC-Set on Student

<table>
<thead>
<tr>
<th>student</th>
<th>Buy_Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>6</td>
</tr>
<tr>
<td>no</td>
<td>3</td>
</tr>
</tbody>
</table>

### AVC-Set on Credit Rating

<table>
<thead>
<tr>
<th>Credit Rating</th>
<th>Buy_Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>6</td>
</tr>
<tr>
<td>fair</td>
<td>6</td>
</tr>
<tr>
<td>excellent</td>
<td>3</td>
</tr>
<tr>
<td>no</td>
<td>4</td>
</tr>
</tbody>
</table>
BOAT (Bootstrapped Optimistic Algorithm for Tree Construction)

- Use a statistical technique called *bootstrapping* to create several smaller samples (subsets), each fits in memory.
- Each subset is used to create a tree, resulting in several trees.
- These trees are examined and used to construct a new tree $T'$.
  - It turns out that $T'$ is very close to the tree that would be generated using the whole data set together.
- Adv: requires only two scans of DB, an incremental alg.
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## Model Evaluation Metrics: Confusion Matrix

### Confusion Matrix:

<table>
<thead>
<tr>
<th>Actual class \ Predicted class</th>
<th>$C_1$</th>
<th>$\neg C_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>True Positives (TP)</td>
<td>False Negatives (FN)</td>
</tr>
<tr>
<td>$\neg C_1$</td>
<td>False Positives (FP)</td>
<td>True Negatives (TN)</td>
</tr>
</tbody>
</table>

### Example of Confusion Matrix:

<table>
<thead>
<tr>
<th>Actual class \ Predicted class</th>
<th>buy_computer = yes</th>
<th>buy_computer = no</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>buy_computer = yes</td>
<td>6954</td>
<td>46</td>
<td>7000</td>
</tr>
<tr>
<td>buy_computer = no</td>
<td>412</td>
<td>2588</td>
<td>3000</td>
</tr>
<tr>
<td>Total</td>
<td>7366</td>
<td>2634</td>
<td>10000</td>
</tr>
</tbody>
</table>

- Given $m$ classes, an entry, $CM_{ij}$ in a confusion matrix indicates the number of tuples in class $i$ that were labeled by the classifier as class $j$.
- May have extra rows/columns to provide totals.
Model Evaluation Metrics: Accuracy, Error Rate, Sensitivity and Specificity

- **Accuracy**, or recognition rate: percentage of test set tuples that are correctly classified

  \[
  \text{Accuracy} = \frac{TP + TN}{\text{All}}
  \]

- **Error rate:** \(1 - \text{accuracy}\), or

  \[
  \text{Error rate} = \frac{FP + FN}{\text{All}}
  \]

- **Class Imbalance Problem:**
  - One class may be *rare*, e.g. fraud, or HIV-positive
  - Significant *majority of the negative class* and minority of the positive class

- **Sensitivity**: True Positive recognition rate (recall for +)
  - \(\text{Sensitivity} = \frac{TP}{P}\)

- **Specificity**: True Negative recognition rate (recall for -)
  - \(\text{Specificity} = \frac{TN}{N}\)

\[
\begin{array}{|c|c|c|c|}
\hline
\text{A} \backslash \text{P} & \text{C} & \neg\text{C} \\
\hline
\text{C} & TP & FN & P \\
\hline
\neg\text{C} & FP & TN & N \\
\hline
P' & N' & \text{All} \\
\hline
\end{array}
\]
Model Evaluation Metrics: Precision and Recall, and F-measures

- **Precision**: exactness – what % of tuples that the classifier (model) labeled as positive are actually positive

\[
\text{precision} = \frac{TP}{TP + FP}
\]

- **Recall**: completeness – what % of positive tuples did the classifier (model) label as positive?

\[
\text{recall} = \frac{TP}{TP + FN}
\]

- Perfect score is 1.0

- Inverse relationship between precision & recall

- **F measure (F₁ or F-score)**: harmonic mean of precision and recall,

\[
F = \frac{2 \times \text{precision} \times \text{recall}}{\text{precision} + \text{recall}}
\]

- **Fβ**: weighted measure of precision and recall
  - assigns β times as much weight to recall as to precision

\[
F_\beta = \frac{(1 + \beta^2) \times \text{precision} \times \text{recall}}{\beta^2 \times \text{precision} + \text{recall}}
\]
## Model Evaluation Metrics: Example

<table>
<thead>
<tr>
<th>Actual Class\Predicted class</th>
<th>cancer = yes</th>
<th>cancer = no</th>
<th>Total</th>
<th>Recognition(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cancer = yes</td>
<td>90</td>
<td>210</td>
<td>300</td>
<td>30.00 (sensitivity)</td>
</tr>
<tr>
<td>cancer = no</td>
<td>140</td>
<td>9560</td>
<td>9700</td>
<td>98.56 (specificity)</td>
</tr>
<tr>
<td>Total</td>
<td>230</td>
<td>9770</td>
<td>10000</td>
<td>96.40 (accuracy)</td>
</tr>
</tbody>
</table>

- **Precision** = $\frac{90}{230} = 39.13\%$
- **Recall** = $\frac{90}{300} = 30.00\%$
Evaluating Learning Algorithm: Holdout & Cross-Validation Methods

- **Holdout method**
  - Given data is randomly partitioned into two independent sets
    - Training set (e.g., 2/3) for model construction
    - Testing set (e.g., 1/3) for accuracy (or another metric) estimation
  - Random sampling: a variation of holdout
    - Repeat holdout k times, accuracy = avg. of the accuracies obtained

- **Cross-validation** (*k*-fold, where *k* = 10 is most common)
  - Randomly partition the data into *k* mutually exclusive subsets, each approximately equal size
  - At *i*-th iteration, use \( D_i \) as testing set and others as training set
  - Leave-one-out: *k* folds where *k* = # of tuples, for small sized data
  - Stratified cross-validation: folds are stratified so that class dist. in each fold is approx. the same as that in the initial data
Evaluating Classifier Accuracy: Bootstrap

- **Bootstrap**
  - Works well with small data sets
  - Samples the given training tuples uniformly *with replacement*
    - i.e., each time a tuple is selected, it is equally likely to be selected again and re-added to the training set
  - Several bootstrap methods, and a common one is **.632 bootstrap**
    - A data set with \(d\) tuples is sampled \(d\) times, with replacement, resulting in a training set of \(d\) samples. The data tuples that did not make it into the training set end up forming the test set. About 63.2\% of the original data end up in the bootstrap, and the remaining 36.8\% form the test set (since \((1 - 1/d)^d \approx e^{-1} = 0.368)\)
    - Repeat the sampling procedure \(k\) times, overall accuracy of the model:

\[
Acc(M) = \frac{1}{k} \sum_{i=1}^{k} (0.632 \times Acc(M_{test\_set}) + 0.368 \times Acc(M_{train\_set}))
\]
Model Selection: ROC Curves

- **ROC** (Receiver Operating Characteristics) curves: for visual comparison of classification models
- Originated from signal detection theory
- Shows the trade-off between the true positive rate and the false positive rate
- The area under the ROC curve is a measure of the accuracy of the model
- Rank the test tuples in decreasing order: the one that is most likely to belong to the positive class appears at the top of the list
- The closer to the diagonal line (i.e., the closer the area is to 0.5), the less accurate is the model
- Vertical axis represents the true positive rate
- Horizontal axis rep. the false positive rate
- The plot also shows a diagonal line
- A model with perfect accuracy will have an area of 1.0
Model Selection Issues

- **Accuracy**
  - classifier accuracy: predicting class label

- **Speed**
  - time to construct the model (training time)
  - time to use the model (classification/prediction time)

- **Robustness**: handling noise and missing values

- **Scalability**: efficiency in disk-resident databases

- **Interpretability**
  - understanding and insight provided by the model
  - Model (e.g., decision tree) size or compactness
Chapters 8-9. Classification

- Classification: Basic Concepts
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- Techniques to Improve Classification
- Lazy Learners (ch9)
- Other known methods: SVM, ANN (ch9)
Using IF-THEN Rules for Classification

- Represent knowledge in the form of IF-THEN rules
  
  R: IF age = youth AND student = yes THEN buys_computer = yes
  
- Rule antecedent/precondition vs. rule consequent

- Assessment of a rule: coverage and accuracy
  
  - \( n_{\text{covers}} = \# \text{ of tuples covered by } R \)
  
  - \( n_{\text{correct}} = \# \text{ of tuples correctly classified by } R \)

  \[
  \text{coverage}(R) = \frac{n_{\text{covers}}}{|D|} \\
  \text{accuracy}(R) = \frac{n_{\text{correct}}}{n_{\text{covers}}}
  \]

- If more than one rule are triggered, need conflict resolution

  - Size ordering: assign the highest priority to the triggering rules that have the “toughest” requirement (i.e., with the most attribute tests)

  - Class-based ordering: decreasing order of prevalence or misclassification cost per class

  - Rule-based ordering (decision list): rules are organized into one long priority list, according to some measure of rule quality or by experts
Rule Extraction from Decision Tree

- A root-to-leaf path corresponds to a rule
  - Each attribute-value pair along a path forms a conjunction: the leaf holds the class prediction
- Rules are exhaustive and mutually exclusive

Example: Rule extraction from our `buys_computer` decision-tree

- IF `age = young` AND `student = no` THEN `buys_computer = no`
- IF `age = young` AND `student = yes` THEN `buys_computer = yes`
- IF `age = mid-age` THEN `buys_computer = yes`
- IF `age = old` AND `credit_rating = excellent` THEN `buys_computer = no`
- IF `age = old` AND `credit_rating = fair` THEN `buys_computer = yes`
Rule Induction: Sequential Covering Method

- Sequential covering: Extracts rules directly from training data
- Typical sequential covering algorithms: FOIL, AQ, CN2, RIPPER
- Rules are learned *sequentially*, each for a given class $C_i$ will cover many tuples of $C_i$ but none (or few) of the tuples of other classes
- Steps:
  - Rules are learned one at a time
  - Each time a rule is learned, the covered positive tuples are removed
  - Repeat until *termination condition* is met. e.g., no more training examples or the quality of a rule generated is below a user-specified threshold

- Unlike decision-trees that learn a set of rules *simultaneously*
Sequential Covering Algorithm

\[\textbf{while} \ (\text{enough target tuples left})\]
\begin{itemize}
  \item generate a rule
  \item remove positive target tuples satisfying this rule
\end{itemize}
How to Learn One Rule?

- Start with the *most general rule* possible: condition = empty
- *Adding new attributes* by adopting a greedy depth-first strategy
  - Picks the one that most improves the rule quality
- Rule-Quality measures: consider both coverage and accuracy
  - Foil-gain (in FOIL & RIPPER): assesses info_gain by extending condition
    \[
    FOIL\_Gain = pos' \times \left( \log_2 \frac{pos'}{pos' + neg'} - \log_2 \frac{pos}{pos + neg} \right)
    \]
    - favors rules that have high accuracy and cover many positive tuples
- Rule pruning based on an independent set of test tuples
  \[
  FOIL\_Prune(R) = \frac{pos - neg}{pos + neg}
  \]
  Pos/neg are # of positive/negative tuples covered by R.
  If *FOIL\_Prune* is higher for the pruned version of R, prune R
Learn one rule

- To generate a rule
  
  \textbf{while}(true)
  
  find the best predicate $p$
  
  \textbf{if} foil-gain($p$) > threshold \textbf{then} add $p$ to current rule
  
  \textbf{else} break
Trees and rules

- Most tree learners: divide and conquer
- Most rule learners: separate and conquer, i.e., sequential covering, (AQ, CN2, RIPPER ...)
  - Some conquering-without-separating (RISE, from Domingos, biased towards complex models), rules are learned simultaneously, instance-based

- Decision space, decision boundary

- Both are interpretable classifiers
- Other usage of rule learning: rule extraction, e.g., from ANN
Separate and conquer vs. set cover

- **Set covering problem (minimum set cover):** one of the most studied combinatorial optimization problems
  - Given a finite ground set $X$ and $S_1, S_2, \ldots, S_m$ as subsets of $X$, find $I \subseteq \{1, \ldots, m\}$ with $\cup_{i \in I} S_i = X$ such that $|I|$ is minimized.
  - Select as few as possible subsets from a given family such that each element in any subset of the family is covered
  - NP-hard

- **Greedy algorithm:** iteratively pick the subset that covers the maximum number of uncovered elements
  - Achieves $1 + \ln n$ approximation ratio, optimal

- **Greedy set cover vs. sequential covering**
  - Select one subset (learn one rule) at a time
  - Consider uncovered elements (remove covered examples)
  - Iterate until all elements (examples) are covered

- Other related problems: graph coloring, minimum clique partition
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Bayesian Classification: Why?

- A statistical classifier: performs *probabilistic prediction*, i.e., predicts class membership probabilities.
- **Foundation**: Based on Bayes’ Theorem.
- **Performance**: A simple Bayesian classifier, *naïve Bayesian classifier*, has comparable performance with decision tree and selected neural network classifiers.
- **Incremental**: Each training example can incrementally increase/decrease the probability that a hypothesis is correct — prior knowledge can be combined with observed data.
- **Standard**: Even when Bayesian methods are computationally intractable, they can provide a standard of optimal decision making against which other methods can be measured.
Probability Model for Classifiers

- Let \( \mathbf{X} = (x_1, x_2, ..., x_n) \) be a data sample ("evidence"): class label is unknown.

- The probability model for a classifier is to determine \( P(C|\mathbf{X}) \), the probability that \( \mathbf{X} \) belongs to class \( C \) given the observed data sample \( \mathbf{X} \).
  - predicts \( \mathbf{X} \) belongs to \( C_i \) iff the probability \( P(C_i|\mathbf{X}) \) is the highest among all the \( P(C_k|\mathbf{X}) \) for all the \( k \) classes.
Bayes’ Theorem

\[ P(C | X) = \frac{P(C)P(X | C)}{P(X)} \]

- \( P(C | X) \): posterior
- \( P(C) \): prior, the initial probability
  - E.g., one will buy computer, regardless of age, income, ...
- \( P(X) \): probability that the sample \( X \) is observed
- \( P(X | C) \): likelihood, probability of observing the sample \( X \), given that the hypothesis holds
  - E.g., Given that \( X \) will buy computer, the prob. that \( X \) is 31..40, medium income
- Informally, this can be written as
  
  \[
  \text{posterior} = \frac{\text{prior} \times \text{likelihood}}{\text{evidence}}
  \]
Maximizing joint probability

\[ P(C|X) = \frac{P(C)P(X|C)}{P(X)} \]

- In practice we are only interested in the numerator of that fraction, since the denominator does not depend on \( H \) and the same value is shared by all classes.

- The numerator is the joint probability

\[ P(C)P(X|C) = P(C,X) = P(C,X_1,X_2,...,X_n) \]
Maximizing joint probability

\[ P(C)P(X|C) = P(C, X) = P(C, X_1, X_2, ... X_n) \]

repeatedly apply conditional probability, \( P(A | B) = \frac{P(A \cap B)}{P(B)} \).

\[
= P(C)P(X_1, X_2, ... X_n | C) \\
= P(C)P(X_1 | C)P(X_2, ... X_n | C, X_1) \\
= P(C)P(X_1 | C)P(X_2 | C, X_1)P(X_3, ... X_n | C, X_1, X_2) \\
= P(C)P(X_1 | C)P(X_2 | C, X_1) ... P(X_n | C, X_1, X_2, ... X_{n-1})
\]
Naïve Bayes Classifier: Assuming Conditional Independence

Simplifying assumption: features are conditionally independent of each other, then,

\[ P(X_i|C, X_j) = P(X_i|C), \quad P(B|A) = P(B). \]

then,

\[
\begin{align*}
P(C, X_1, X_2, \ldots X_n) &= P(C)P(X_1|C)P(X_2|C, X_1)\ldots P(X_n|C, X_1, X_2, \ldots X_{n-1}) \\
&= P(C)P(X_1|C)P(X_2|C)\ldots P(X_n|C)
\end{align*}
\]

This greatly reduces the computation cost: Only counts the class distribution.
Naïve Bayes Classifier

- This greatly reduces the computation cost: Only counts the class distribution
- If $A_k$ is categorical, $P(x_k | C_i)$ is the # of tuples in $C_i$ having value $x_k$ for $A_k$ divided by $|C_{i,D}|$ (# of tuples of $C_i$ in $D$)
- If $A_k$ is continuous-valued, $P(x_k | C_i)$ is usually computed based on Gaussian distribution with a mean $\mu$ and standard deviation $\sigma$

and $P(x_k | C_i)$ is

$$g(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

$$P(X \mid C_i) = g(x_k, \mu_{C_i}, \sigma_{C_i})$$
Naïve Bayes Classifier: Training Dataset

Class:
C1:buys_computer = ‘yes’
C2:buys_computer = ‘no’

Data to be classified:
X = (age <=30,
Income = medium,
Student = yes
Credit_rating = Fair)

<table>
<thead>
<tr>
<th>age</th>
<th>income</th>
<th>student</th>
<th>credit_rating</th>
<th>buys_computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;=30</td>
<td>high</td>
<td>no</td>
<td>fair</td>
<td>no</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>high</td>
<td>no</td>
<td>excellent</td>
<td>no</td>
</tr>
<tr>
<td>31…40</td>
<td>high</td>
<td>no</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>medium</td>
<td>no</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>low</td>
<td>yes</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>low</td>
<td>yes</td>
<td>excellent</td>
<td>no</td>
</tr>
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<td>yes</td>
</tr>
<tr>
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<td>medium</td>
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<td>fair</td>
<td>no</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>low</td>
<td>yes</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&gt;40</td>
<td>medium</td>
<td>yes</td>
<td>fair</td>
<td>yes</td>
</tr>
<tr>
<td>&lt;=30</td>
<td>medium</td>
<td>yes</td>
<td>excellent</td>
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<td>no</td>
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<td>medium</td>
<td>yes</td>
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<td>&gt;40</td>
<td>medium</td>
<td>no</td>
<td>excellent</td>
<td>no</td>
</tr>
</tbody>
</table>
Naïve Bayes Classifier: Example

- **X** = (age <= 30, income = medium, student = yes, credit_rating = fair)

- **P(C):**
  - P(buys_computer = “yes”) = 9/14 = 0.643
  - P(buys_computer = “no”) = 5/14 = 0.357

- Compute P(X|C) for each class
  - P(age = “<=30” | buys_computer = “yes”) = 2/9 = 0.222
  - P(income = “medium” | buys_computer = “yes”) = 4/9 = 0.444
  - P(student = “yes” | buys_computer = “yes”) = 6/9 = 0.667
  - P(credit_rating = “fair” | buys_computer = “yes”) = 6/9 = 0.667

  - P(age = “<= 30” | buys_computer = “no”) = 3/5 = 0.6
  - P(income = “medium” | buys_computer = “no”) = 2/5 = 0.4
  - P(student = “yes” | buys_computer = “no”) = 1/5 = 0.2
  - P(credit_rating = “fair” | buys_computer = “no”) = 2/5 = 0.4

- **P(X | C):**
  - P(X|buys_computer = “yes”) = 0.222 x 0.444 x 0.667 x 0.667 = 0.044
  - P(X|buys_computer = “no”) = 0.6 x 0.4 x 0.2 x 0.4 = 0.019

- P(C, X) = P(X | C) x P(C)
  - P(X|buys_computer = “yes”) x P(buys_computer = “yes”) = 0.028
  - P(X|buys_computer = “no”) x P(buys_computer = “no”) = 0.007

Therefore, X belongs to class (“buys_computer = yes”)
Avoiding the Zero-Probability Problem

- Naïve Bayesian prediction requires each conditional prob. be non-zero. Otherwise, the predicted prob. will be zero

\[ P(X \mid C_i) = \prod_{k=1}^{n} P(x_k \mid C_i) \]

- Suppose training set has 1000 tuples for class buys_computer= yes. 0 for income=low, 990 for income=medium, and 10 for income=high

- Use Laplacian correction (or Laplacian estimator)
  - Adding 1 to each case
    - Prob(income = low) = 1/1003
    - Prob(income = medium) = 991/1003
    - Prob(income = high) = 11/1003
  - The “corrected” prob. estimates are close to their “uncorrected” counterparts
Naïve Bayes Classifier: Comments

- **Advantages**
  - Easy to implement
  - Good results obtained in most of the cases

- **Disadvantages**
  - Assumption: class conditional independence, therefore loss of accuracy
  - Practically, dependencies exist among variables
    - E.g., hospitals: patients: Profile: age, family history, etc. Symptoms: fever, cough etc., Disease: lung cancer, diabetes, etc.
    - Dependencies among these cannot be modeled by Naïve Bayes Classifier
  - How to deal with these dependencies? Bayesian Belief Networks (Chapter 9)
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Bayesian Belief Networks

- Bayesian belief network relieves the conditional independence assumption in naïve bayes
- A graphical model of causal relationships
  - Represents dependency among the variables
  - Gives a specification of joint probability distribution

- Nodes: random variables
- Links: dependency
- X and Y are the parents of Z, and Y is the parent of P
- No dependency between Z and P
- Has no loops or cycles
Bayesian Belief Network: An Example

The **conditional probability table** (**CPT**) for variable LungCancer:

<table>
<thead>
<tr>
<th></th>
<th>(FH, S)</th>
<th>(FH, ~S)</th>
<th>(~FH, S)</th>
<th>(~FH, ~S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>0.8</td>
<td>0.5</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>~LC</td>
<td>0.2</td>
<td>0.5</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

CPT shows the conditional probability for each possible combination of its parents.

Derivation of the probability of a particular combination of values of $X$, from CPT:

$$P(x_1, ..., x_n) = \prod_{i=1}^{n} P(x_i | Parents(x_i))$$
Training Bayesian Networks

Several scenarios:

- Given both the network structure and all variables observable: *learn only the CPTs*

- Network structure known, some hidden variables: *gradient descent* (greedy hill-climbing) method, analogous to neural network learning

- Network structure unknown, all variables observable: search through the model space to *reconstruct network topology*

- Unknown structure, all hidden variables: No good algorithms known for this purpose

- Ref. D. Heckerman: Bayesian networks for data mining
Example

- Two events could cause grass to be wet: either the sprinkler is on or it's raining.
- The rain has a direct effect on the use of the sprinkler:
  - when it rains, the sprinkler is usually not turned on.

Then the situation can be modeled with a Bayesian network. All three variables have two possible values, T and F. The joint probability function is:

\[ P(G, S, R) = P(G | S, R)P(S | R)P(R) \]

where \( G = \text{Grass wet} \), \( S = \text{Sprinkler} \), and \( R = \text{Rain} \).
Example

The joint probability function is:

$$P(G,S,R) = P(G | S,R)P(S | R)P(R)$$

where $G = Grass$ wet, $S = Sprinkler$, and $R = Rain$

- The model can answer questions like "What is the probability that it is raining, given the grass is wet?"

$$P(R = T | G = T) = \frac{P(G = T, R = T)}{P(G = T)} = \frac{\sum_{S \in \{T,F\}} P(G = T, S, R = T)}{\sum_{S,R \in \{T,F\}} P(G = T, S, R)}$$

$$= \frac{(0.99 \times 0.01 \times 0.2 = 0.00198_{TTT}) + (0.8 \times 0.99 \times 0.2 = 0.1584_{TFT})}{0.00198_{TTT} + 0.288_{TFF} + 0.1584_{TFT} + 0_{TFF}} \approx 35.77\%.$$
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Ensemble Methods: Increasing the Accuracy

- **Ensemble methods**
  - Use a combination of models to increase accuracy
  - Combine a series of $k$ learned models, $M_1, M_2, \ldots, M_k$, with the aim of creating an improved model $M^*$

- **Popular ensemble methods**
  - Bagging: averaging the prediction over a collection of classifiers
  - Boosting: weighted vote with a collection of classifiers
  - Ensemble: combining a set of heterogeneous classifiers
Bagging: Bootstrap Aggregation

- Analogy: Diagnosis based on multiple doctors’ majority vote
- Training
  - Given a set D of d tuples, at each iteration $i$, a training set $D_i$ of $d$ tuples is sampled with replacement from D (i.e., bootstrap)
  - A classifier model $M_i$ is learned for each training set $D_i$
- Classification: classify an unknown sample $X$
  - Each classifier $M_i$ returns its class prediction
  - The bagged classifier $M^*$ counts the votes and assigns the class with the most votes to $X$
- Prediction: can be applied to the prediction of continuous values by taking the average value of each prediction for a given test tuple
- Accuracy
  - Often significantly better than a single classifier derived from D
  - For noise data: not considerably worse, more robust
  - Proved improved accuracy in prediction
Boosting

- Analogy: Consult several doctors, based on a combination of weighted diagnoses—weight assigned based on the previous diagnosis accuracy

- How boosting works?
  - **Weights** are assigned to each training tuple
  - A series of k classifiers is iteratively learned
  - After a classifier $M_i$ is learned, the weights are updated to allow the subsequent classifier, $M_{i+1}$, to **pay more attention to the training tuples that were misclassified** by $M_i$
  - The final $M^*$ **combines the votes** of each individual classifier, where the weight of each classifier's vote is a function of its accuracy

- Boosting algorithm can be extended for numeric prediction

- Comparing with bagging: Boosting tends to have greater accuracy, but it also risks overfitting the model to misclassified data
Adaboost (Freund and Schapire, 1997)

- Given a set of $d$ class-labeled tuples, $(x_1, y_1), \ldots, (x_d, y_d)$
- Initially, all the weights of tuples are set the same (1/d)
- Generate k classifiers in k rounds. At round i,
  - Tuples from D are sampled (with replacement) to form a training set $D_i$ of the same size
  - Each tuple’s chance of being selected is based on its weight
  - A classification model $M_i$ is derived from $D_i$
  - Its error rate is calculated using $D_i$ as a test set
  - If a tuple is misclassified, its weight is increased, o.w. it is decreased
- Error rate: $\text{err}(x_j)$ is the misclassification error of tuple $x_j$. Classifier $M_i$ error rate is the sum of the weights of the misclassified tuples:
  $$\text{error}(M_i) = \sum_{j=1}^{d} w_j \times \text{err}(x_j)$$
- The weight of classifier $M_i$’s vote is
  $$\log \frac{1 - \text{error}(M_i)}{\text{error}(M_i)}$$
Random Forest (Breiman 2001)

- **Random Forest:**
  - Each classifier in the ensemble is a *decision tree* classifier and is generated using a random selection of attributes at each node to determine the split
  - During classification, each tree votes and the most popular class is returned

- **Two Methods to construct Random Forest:**
  - Forest-RI (*random input selection*): Randomly select, at each node, $F$ attributes as candidates for the split at the node. The CART methodology is used to grow the trees to maximum size
  - Forest-RC (*random linear combinations*): Creates new attributes (or features) that are a linear combination of the existing attributes (reduces the correlation between individual classifiers)

- Comparable in accuracy to Adaboost, but more robust to errors and outliers
- Insensitive to the number of attributes selected for consideration at each split, and faster than bagging or boosting
Classification of Class-Imbalanced Data Sets

- Class-imbalance problem: Rare positive example but numerous negative ones, e.g., medical diagnosis, fraud, oil-spill, fault, etc.
- Traditional methods assume a balanced distribution of classes and equal error costs: not suitable for class-imbalanced data
- Typical methods for imbalance data in 2-class classification:
  - **Oversampling**: re-sampling of data from positive class
  - **Under-sampling**: randomly eliminate tuples from negative class
  - **Threshold-moving**: moves the decision threshold, $t$, so that the rare class tuples are easier to classify, and hence, less chance of costly false negative errors
  - Ensemble techniques: Ensemble multiple classifiers introduced above
- Still difficult for class imbalance problem on multiclass tasks
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- Other known methods: SVM, ANN (ch9)
Lazy vs. Eager Learning

- Lazy vs. eager learning
  - **Lazy learning** (e.g., instance-based learning): Simply stores training data (or only minor processing) and waits until it is given a test tuple
  - **Eager learning** (the above discussed methods): Given a set of training tuples, constructs a classification model before receiving new (e.g., test) data to classify
- Lazy: less time in training but more time in predicting
- Accuracy
  - Lazy method effectively uses a richer hypothesis space since it uses many local linear functions to form an implicit global approximation to the target function
  - Eager: must commit to a single hypothesis that covers the entire instance space
Lazy Learner: Instance-Based Methods

- Instance-based learning:
  - Store training examples and delay the processing ("lazy evaluation") until a new instance must be classified

- Typical approaches
  - $k$-nearest neighbor approach
    - Instances represented as points in a Euclidean space.
  - Locally weighted regression
    - Constructs local approximation
  - Case-based reasoning
    - Uses symbolic representations and knowledge-based inference
The \textit{k}-Nearest Neighbor Algorithm

- All instances correspond to points in the n-D space
- The nearest neighbor are defined in terms of Euclidean distance, $\text{dist}(\mathbf{X}_1, \mathbf{X}_2)$
- Target function could be discrete- or real- valued
- For discrete-valued, $k$-NN returns the most common value among the $k$ training examples nearest to $\mathbf{x}_q$
- Voronoi diagram: the decision surface induced by 1-NN for a typical set of training examples
Discussion on the $k$-NN Algorithm

- $k$-NN for real-valued prediction for a given unknown tuple
  - Returns the mean values of the $k$ nearest neighbors
- **Distance-weighted** nearest neighbor algorithm
  - Weight the contribution of each of the $k$ neighbors according to their distance to the query $x_q$
    - Give greater weight to closer neighbors
  \[
  w = \frac{1}{d(x_q, x_i)^2}
  \]
- Robust to noisy data by averaging $k$-nearest neighbors
- **Curse of dimensionality**: distance between neighbors could be dominated by irrelevant attributes
  - To overcome it, axes stretch or elimination of the least relevant attributes
Chapters 8-9. Classification

- Classification: Basic Concepts
- Decision Tree Induction
- Model Evaluation/Learning Algorithm Evaluation
- Rule-Based Classification
- Bayes Classification Methods
- Bayesian Belief Networks (ch9)
- Techniques to Improve Classification
- Lazy Learners (ch9)
- Other known methods: SVM, ANN (ch9)
SVM—Support Vector Machines

- A new classification method for both linear and nonlinear data
- It uses a nonlinear mapping to transform the original training data into a higher dimension
- With the new dimension, it searches for the linear optimal separating hyperplane (i.e., “decision boundary”)
- With an appropriate nonlinear mapping to a sufficiently high dimension, data from two classes can always be separated by a hyperplane
- SVM finds this hyperplane using support vectors (“essential” training tuples) and margins (defined by the support vectors)
History and Applications

- Vapnik and colleagues (1992)—groundwork from Vapnik & Chervonenkis’ statistical learning theory in 1960s
- Features: training can be slow but accuracy is high owing to their ability to model complex nonlinear decision boundaries (margin maximization)
- Used both for classification and prediction
- Applications:
  - handwritten digit recognition, object recognition, speaker identification, benchmarking time-series prediction tests
General Philosophy

Small Margin

Large Margin

Support Vectors
Let data $D$ be $(X_1, y_1), \ldots, (X_{|D|}, y_{|D|})$, where $X_i$ is the set of training tuples associated with the class labels $y_i$.

There are infinite lines (hyperplanes) separating the two classes but we want to find the best one (the one that minimizes classification error on unseen data).

SVM searches for the hyperplane with the largest margin, i.e., maximum marginal hyperplane (MMH).
Kernel functions

- Instead of computing the dot product on the transformed data tuples, it is mathematically equivalent to instead applying a kernel function $K(X_i, X_j)$ to the original data, i.e., $K(X_i, X_j) = \Phi(X_i) \Phi(X_j)$
- Typical Kernel Functions

  Polynomial kernel of degree $h$: $K(X_i, X_j) = (X_i \cdot X_j + 1)^h$

  Gaussian radial basis function kernel: $K(X_i, X_j) = e^{-\|X_i - X_j\|^2 / 2\sigma^2}$

  Sigmoid kernel: $K(X_i, X_j) = \tanh(\kappa X_i \cdot X_j - \delta)$

- SVM can also be used for classifying multiple (> 2) classes and for regression analysis (with additional user parameters)
Why Is SVM Effective on High Dimensional Data?

- The complexity of trained classifier is characterized by the # of support vectors rather than the dimensionality of the data.
- The support vectors are the essential or critical training examples — they lie closest to the decision boundary (MMH).
- If all other training examples are removed and the training is repeated, the same separating hyperplane would be found.
- The number of support vectors found can be used to compute an (upper) bound on the expected error rate of the SVM classifier, which is independent of the data dimensionality.
- Thus, an SVM with a small number of support vectors can have good generalization, even when the dimensionality of the data is high.
SVM—Introduction Literature

- “Statistical Learning Theory” by Vapnik: extremely hard to understand, containing many errors too.
  - Better than the Vapnik’s book, but still written too hard for introduction, and the examples are so not-intuitive
- The book “An Introduction to Support Vector Machines” by N. Cristianini and J. Shawe-Taylor
  - Also written hard for introduction, but the explanation about the mercer’s theorem is better than above literatures
- The neural network book by Haykins
  - Contains one nice chapter of SVM introduction
SVM Related Links

- SVM Website
  - http://www.kernel-machines.org/

- Representative implementations
  - LIBSVM: an efficient implementation of SVM, multi-class classifications, nu-SVM, one-class SVM, including also various interfaces with java, python, etc.
  - SVM-light: simpler but performance is not better than LIBSVM, support only binary classification and only C language
  - SVM-torch: another recent implementation also written in C.
An artificial neural network is an interconnected group of nodes, akin to the vast network of neurons in a brain. Here, each circular node represents an artificial neuron and an arrow represents a connection from the output of one neuron to the input of another.

Deep learning: deep neural networks
SVM vs. ANN

- **SVM**
  - Relatively new concept
  - Deterministic
  - Nice Generalization properties
  - Hard to learn – learned in batch mode using quadratic programming techniques
  - Using kernels can learn very complex functions

- **ANN**
  - Relatively old (but ...)
  - Nondeterministic
  - Generalizes well but doesn’t have strong mathematical foundation
  - Can easily be learned in incremental fashion
  - To learn complex functions—use multilayer perceptron (not that trivial)