Data Mining II
Ensembles

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Introduction

- “Wisdom of the crowds”
  - a single individual cannot know everything
  - but together, a group of individuals knows a lot

- Examples
  - Wikipedia
  - Crowdsourcing
  - Prediction

http://xkcd.com/903/
Introduction

- “SPIEGEL Wahlwette” (election bet) 2013
  - readers of SPIEGEL Online were asked to guess the federal election results
  - average across all participants:
    - only a few percentage points error for final result
    - conservative-liberal coalition cannot continue

https://lh6.googleusercontent.com/-U9DXTTcT-PM/UgsdSzdV3JI/AAAAAAAAFKs/GsRydeldasg/w800-h800/Bildschirmfoto+2013-08-14+um+07.56.01.png
Introduction

• “Who wants to be a Millionaire?”

• Analysis by Franzen and Pointner (2009):
  – “ask the audience” gives a correct majority result in 89% of all cases
  – “telephone expert”: only 54%
Ensembles

• So far, we have addressed a learning problem like this:

```python
classifier = DecisionTreeClassifier(max_depth=5)
...and hoped for the best
```

• Ensembles:
  – wisdom of the crowds for learning operators
  – instead of asking a single learner, combine the predictions of different learners
Ensembles

• Prerequisites for ensembles: accuracy and diversity
  – different learning operators can address a problem (accuracy)
  – different learning operators make different mistakes (diversity)

• That means:
  – predictions on a new example may differ
  – if one learner is wrong, others may be right

• Ensemble learning:
  – use various base learners
  – combine their results in a single prediction
Voting

• The most straightforward approach
  – classification: use most-predicted label
  – regression: use average of predictions

• We have already seen this
  – k-nearest neighbors
  – each neighbor can be regarded as an individual classifier
Voting in RapidMiner & SciKit Learn

- **RapidMiner**: Vote operator uses different base learners
- **Python**: `VotingClassifier(
  ("dt", DecisionTreeClassifier(),
  "nb", GaussianNB(),
  "knn", KNeighborsClassifier()))`
Performance of Voting

- Accuracy in this example:
  - Naive Bayes: 0.71
  - Ripper: 0.71
  - k-NN: 0.81
- Voting: 0.91
Why does Voting Work?

• Suppose there are 25 base classifiers
  – Each classifier has an accuracy of 0.65, i.e., error rate $\varepsilon = 0.35$
  – Assume classifiers are independent
    • i.e., probability that a classifier makes a mistake does not depend on whether other classifiers made a mistake
    • Note: in practice they are not independent!

• Probability that the ensemble classifier makes a wrong prediction
  – The ensemble makes a wrong prediction if the majority of the classifiers makes a wrong prediction
  – The probability that 13 or more classifiers are wrong is

$$\sum_{i=13}^{25} \binom{25}{i} \varepsilon^i (1-\varepsilon)^{25-i} \approx 0.06 \ll \varepsilon$$
Why does Voting Work?

• In theory, we can lower the error infinitely just by adding more base learners
  – But that is hard in practice
    – Why?

• The formula only holds for independent base learners
  – It is hard to find many truly independent base learners
  – ...at a decent level of accuracy

• Recap: we need both accuracy and diversity

\[
\sum_{i=13}^{25} \binom{25}{i} \varepsilon^i (1-\varepsilon)^{25-i} \approx 0.06 \ll \varepsilon
\]
Recap: Overfitting and Noise

Likely to overfit the data
Bagging

- Biases in data samples may mislead classifiers
  - overfitting problem
  - model is overfit to single noise points

- If we *had* different samples
  - e.g., data sets collected at different times, in different places, …
  - ...and trained a single model on each of those data sets...
  - only one model would overfit to each noise point
  - voting could help address these issues

- But usually, we only have one dataset!
Bagging

- Models may differ when learned on different data samples
- Idea of bagging:
  - create samples by picking examples *with replacement*
  - learn a model on each sample
  - combine models
- Usually, the same base learner is used
- Samples
  - differ in the subset of examples
  - replacement randomly re-weights instances (see later)
Bagging: illustration

Training Data

Data1 → Learner1 → Model1

Data2 → Learner2 → Model2

... → ... → ...

Data m → Learner m → Model m

Model Combiner

Final Model
Bagging: Generating Samples

- Generate new training sets using sampling with replacement (bootstrap samples)

<table>
<thead>
<tr>
<th>Original Data</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagging (Round 1)</td>
<td>7</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Bagging (Round 2)</td>
<td>1</td>
<td>4</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Bagging (Round 3)</td>
<td>1</td>
<td>8</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

- some examples may appear in more than one set
- some examples will appear more than once in a set
- for each set of size $n$, the probability that a given example appears in it is

$$\Pr(x \in D_i) = 1 - \left(1 - \frac{1}{n}\right)^n \rightarrow 0.6322$$

- i.e., on average, less than $2/3$ of the examples appear in any single bootstrap sample
Bagging in RapidMiner and Python

- Bagging operator uses a base learner
- Number and ratio of samples can be specified
  - `bagging = BaggingClassifier(DecisionTreeClassifier(), 10, 0.5)`
Performance of Bagging

- Accuracy in this example:
  - Ripper alone: 0.71
  - Ripper with bagging (10x0.5): 0.86
Bagging in RapidMiner

- 10 different rule models are learned:

```
RuleModel
if attribute_12 ≤ 0.168 and attribute_25 > 0.553 then Rock  (28 / 0)
if attribute_28 > 0.854 then Mine   (2 / 23)
if attribute_31 ≤ 0.443 and attribute_30 > 0.246 then Mine  (0 / 16)
if attribute_4 ≤ 0.061 then Rock   (16 / 0)
else Mine   (2 / 5)
```
correct: 88 out of 92 training examples.
Variant of Bagging: Randomization

• Randomize the learning algorithm instead of the input data
• Some algorithms already have a random component
  – e.g. initial weights in neural net
• Most algorithms can be randomized, e.g., greedy algorithms:
  – Pick from the $N$ best options at random instead of always picking the best options
  – e.g.: test selection in decision trees or rule learning
• Can be combined with bagging
Random Forests

• A variation of bagging with decision trees
• Train a number of individual decision trees
  – each on a random subset of examples
  – only analyze a random subset of attributes for each split
    (Recap: classic DT learners analyze all attributes at each split)
  – usually, the individual trees are left unpruned

rf = RandomForestClassifier(n_estimators=10)
Paradigm Shift: Many Simple Learners

• So far, we have looked at learners that are as good as possible

• Bagging allows a different approach
  – several simple models instead of a single complex one
  – Analogy: the SPIEGEL poll (mostly no political scientists, nevertheless: accurate results)
  – extreme case: using only decision stumps

• Decision stumps:
  – decision trees with only one node
Bagging with Weighted Voting

- Some learners provide confidence values
  - e.g., decision tree learners
  - e.g., Naive Bayes

- Weighted voting
  - use those confidence values for weighting the votes
  - some models may be rather sure about an example, while others may be indifferent
  - Python: parameter `voting=soft`
    - sums up all confidences for each class and predicts argmax
    - caution: requires *comparable* confidence scores!
Weighted Voting with Decision Stumps

- Weights: confidence values in each leaf

  ![Decision Stump Diagram]

  - High confidence that it is rock (weight = 1.0)
  - Lower confidence that it is mine (weight = 0.6)
Intermediate Recap

• What we've seen so far
  – ensembles often perform better than single base learners
  – simple approach: voting, bagging

• More complex approaches coming up
  – Boosting
  – Stacking

• Boosting requires learning with *weighted instances*
  – we'll have a closer look at that problem first
Intermezzo: Learning with Weighted Instances

• So far, we have looked at learning problems where each example is equally important

• Weighted instances
  – assign each instance a weight (*think*: importance)
  – getting a high-weighted instance wrong is more expensive
  – accuracy etc. can be adapted

• Example:
  – data collected from different sources (e.g., sensors)
  – sources are not equally reliable
    • we want to assign more weight to the data from reliable sources
Intermezzo: Learning with Weighted Instances

• Two possible strategies of dealing with weighted instances

• Changing the learning algorithm
  – e.g., decision trees, rule learners: adapt splitting/rule growing heuristics, example on following slides

• Duplicating instances
  – an instance with weight \( n \) is copied \( n \) times
  – simple method that can be used on all learning algorithms
Recap: Accuracy

- Most frequently used metrics:

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

Error Rate = 1 – Accuracy
Accuracy with Weights

- Definition of accuracy

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

- Without weights, TP, FP etc. are \textit{counts} of instances

- With weights, they are \textit{sums of their weights}
  - classic TP, FP etc. are the special case where all weights are 1
Adapting Algorithms: Decision Trees

• Recap: Gini index as splitting criterion

\[
\text{GINI}(t) = 1 - \sum_{j} [p(j \mid t)]^2
\]

• The probabilities are obtained by counting examples
  – Again, we can sum up weights instead

• The same works for rule-based classifiers and their heuristics
Adapting Algorithms: k-NN

• Standard approach
  – use average of neighbor predictions

• With weighted instances
  – weighted average
Intermezzo: Learning with Weighted Instances

• Handling imbalanced classification problems

• So far:
  – undersampling
    • removes examples → loss of information
  – oversampling
    • adds examples → larger data (performance!)
    • also: synthetic data points (SMOTE)

• Alternative:
  – lowering instance weights for larger class
  – simplest approach: weight $1/|C|$ for each instance in class C
Back to Ensembles: Boosting

• Idea of boosting
  – train a set of classifiers, one after another
  – later classifiers focus on examples that were misclassified by earlier classifiers
  – weight the predictions of the classifiers with their error

• Realization
  – perform multiple iterations
    • each time using different example weights
  – weight update between iterations
    • *increase* the weight of *incorrectly* classified examples
    • so they become more important in the next iterations (misclassification errors for these examples count more heavily)
  – combine results of all iterations
    • weighted by their respective error measures
1. Initialize example weights $w_i = 1/N \ (i = 1..N)$

2. For $m = 1$ to $t$ // $t$ … number of iterations
   a) Learn a classifier $C_m$ using the current example weights
   b) Compute a weighted error estimate $err_m = \frac{\sum w_i \text{of all incorrectly classified } e_i}{\sum_{i=1}^{N} w_i}$

   c) If $err_m > 0.5$ → exit loop
   d) Compute a classifier weight $\alpha_m = \frac{1}{2} \ln \left( \frac{1 - err_m}{err_m} \right)$
   e) For all correctly classified examples $e_i$: $w_i \leftarrow w_i e^{-\alpha_m}$
   f) For all incorrectly classified examples $e_i$: $w_i \leftarrow w_i e^{\alpha_m}$
   g) Normalize the weights $w_i$ so that they sum to $1$

3. For each test example
   a) Try all classifiers $C_m$
   b) Predict the class that receives the highest sum of weights $\alpha_m$
Illustration of the Weights

- Classifier Weights $\alpha_m$
  - differences near 0 or 1 are emphasized
- Good classifier
  $\rightarrow$ highly positive weight
- Bad classifier
  $\rightarrow$ highly negative weight
- Classifier with error 0.5
  $\rightarrow$ weight 0
  $\rightarrow$ this is equal to guessing!
Illustration of the Weights

- Example Weights
  - multiplier for correct and incorrect examples
  - depending on error
- Later iterations need to focus on examples that are
  - Incorrectly classified by a good classifier
  - Correctly classified by a bad classifier
Boosting – Error Rate Example

- boosting of decision stumps on simulated data

from Hastie, Tibshirani, Friedman: The Elements of Statistical Learning, Springer Verlag 2001
Toy Example

\[ D_1 \]

(taken from Verma & Thrun, Slides to CALD Course CMU 15-781, Machine Learning, Fall 2000)
Round 1

\[ h_1 \]

\[ \varepsilon_1 = 0.30 \]
\[ \alpha_1 = 0.42 \]

\[ D_2 \]
Round 2

\[ \varepsilon_2 = 0.21 \]
\[ \alpha_2 = 0.65 \]
Round 3

\[ h_3 \]

\[ \varepsilon_3 = 0.14 \]

\[ \alpha_3 = 0.92 \]
$H_{\text{final}} = \text{sign} \left( \begin{array}{c} 0.42 \end{array} \right) + 0.65 + 0.92$
Hypothesis Space of Ensembles

• Each learner has a *hypothesis space*
  – e.g., decision stumps: a linear separation of the dataset, parallel to the axes

• The hypothesis space of an ensemble
  – can be larger than that of its base learners

• Example: bagging with decision stumps
  – different stumps → different linear separations
  – resulting hypothesis space also allows polygon separations
Boosting in RapidMiner and Python

• Just like voting and bagging
  
  ```python
  bdt = AdaBoostClassifier(DecisionTreeClassifier(), n_estimators=200)
  ```
Experimental Results on Ensembles

- Ensembles have been used to improve generalization accuracy on a wide variety of problems.
- On average, Boosting provides a larger increase in accuracy than Bagging:
  - Boosting on rare occasions can degrade accuracy.
  - Bagging more consistently provides a modest improvement.
- Boosting is particularly subject to over-fitting when there is significant noise in the training data:
  - Subsequent learners over-focus on noise points.

(Freund & Schapire, 1996; Quinlan, 1996)
Back to Combining Predictions

• Voting
  – each ensemble member votes for one of the classes
  – predict the class with the highest number of vote (e.g., bagging)

• Weighted Voting
  – make a *weighted* sum of the votes of the ensemble members
  – weights typically depend
    • on the classifier's confidence in its prediction
      (e.g., the estimated probability of the predicted class)
    • on error estimates of the classifier (e.g., boosting)

• Stacking
  – Why not use a classifier for making the final decision?
  – training material are the class labels of the training data and the
    (cross-validated) predictions of the ensemble members
Stacking

- Basic Idea:
  - learn a function that combines the predictions of the individual classifiers
- Algorithm:
  - train $n$ different classifiers $C_1...C_n$ (the base classifiers)
  - obtain predictions of the classifiers for the training examples
  - form a new data set (the meta data)
    - **classes**
      - the same as the original dataset
    - **attributes**
      - one attribute for each base classifier
      - value is the prediction of this classifier on the example
  - train a separate classifier $M$ (the meta classifier)
Stacking (2)

- Example:

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{11}$</td>
<td>$t$</td>
</tr>
<tr>
<td>$x_{21}$</td>
<td>$f$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$x_{n_{e1}}$</td>
<td>$t$</td>
</tr>
</tbody>
</table>

Using a stacked classifier:
- try each of the classifiers $C_1 \ldots C_n$
- form a feature vector consisting of their predictions
- submit these feature vectors to the meta classifier $M$
Stacking and Overfitting

• Consider a dumb base learner D, which works as follows:
  – during training: store each training example
  – during classification: if example is stored, return its class
    otherwise: return a random prediction

• If D is used along with a number of classifiers in stacking, what will the meta classifier look like?
  – D is perfect on the training set
  – so the meta classifier will say: always use D's result

Implementation in RapidMiner :-(

do you know that classifier?
Stacking and Overfitting

- **Solution 1:** split dataset (e.g., 50/50)
  - use one portion for training the base classifiers
  - use other portion to train meta model

- **Solution 2:** cross-validate base classifiers
  - train classifier on 90% of training data
  - create features for the remaining 10% on that classifier
  - repeat 10 times

- The second solution is better in most cases
  - uses whole dataset for meta learner
  - uses 90% of the dataset for base learners
Stacking in RapidMiner and Python

• Looks familiar again
  – we need a set of base learners (like for voting)
  – and a learner for the stacking model
• Python: not in scikit-learn, use, e.g., package mlxtend
  – requires setting base classifiers and meta learner as well
Performance of Stacking

• Accuracy in this experiment:
  – Naive Bayes: 0.71
  – k-NN: 0.81
  – Ripper: 0.71

• Stacked model: 0.86
Stacking

- Variant: also keep the original attributes
- Predictions of base learners are additional attributes for the stacking predictor
  - allows the identification of “blind spots” of individual base learners

- Variant: stacking with confidence values
  - if learners output confidence values, those can be used by the stacking learner
  - often further improves the results
The Classifier Selection Problem

- Question: decision trees or rule learner – which one is better?
- Two corner cases – recap from Data Mining 1

Accuracy:
- Baseline: 0.45
- Decision Tree: 0.45
- Rule Learner: 0.7
- Voting: 0.65
- Weighted Voting: 0.7
- Stacking: 0.83

Accuracy:
- Baseline: 0.89
- Decision Tree: 1.0
- Rule Learner: 0.89
- Voting: 0.89
- Weighted Voting: 1.0
- Stacking: 1.0
Regression Ensembles

• Most ensemble methods also work for regression
  – voting: use average
  – bagging: use average or weighted average
  – stacking: learn regression model as stacking model!
  – boosting: the regression variant is called additive regression

• In Python: usually the same class ending in Regressor instead of Classifier
Additive Regression

- Boosting can be seen as a greedy algorithm for fitting additive models
- Same kind of algorithm for numeric prediction:
  - Build standard regression model
  - Gather residuals, learn model predicting residuals, and repeat
    • Given a prediction $p(x)$, residual $= (x-p(x))^2$
- To predict, simply sum up weighted individual predictions from all models
Additive Regression w/ Linear Regression

• What happens if we use Linear Regression inside of Additive Regression?

• The first iteration learns a linear regression model $lr_1$
  – By minimizing the sum of squared errors

• The second iteration aims at learning a LR $lr_2$ model for
  – $x' = (x - lr_1(x))^2$
  – Since $(x - lr_1(x))^2$ is already minimal, $lr_2$ cannot improve upon this
    • Hence, the subsequent linear models will always be a constant 0
Additive Regression w/ Linear Regression

- First regression model:
Additive Regression w/ Linear Regression

- Second (and third, fourth, ...) regression model:
Additive Regression

• Bottom line: additive and linear regression are not a good match
Example 1: One-dimensional, Non-linear

Linear Regression: RMSE = 0.199

Isotonic Regression: RMSE = 0.171

Additive Isotonic Regression: RMSE = 0.073
Example 2: Multidimensional, Non-Linear

- \[ z = 10x^2 - y^3 \]

RMSE of...
- Linear Regression: 385
- Isotonic Regression: 293
- Additive Isotonic Regression: 122
XGBoost

• Currently wins most Kaggle competitions etc.
• Additive Regression w/ Regression Trees
• Regularization
  – Respect size of trees
  – Larger trees: more likely to overfit!
    • Introduce penalty for tree size
  – Overcomes the problem of overfitting in boosting
Intermediate Recap

• Ensemble methods
  – outperform base learners
  – Help minimizing shortcomings of single learners/models
  – simple and complex methods for method combination

• Reasons for performance improvements
  – individual errors of single learners can be “outvoted”
  – more complex hypothesis space
Ensembles for Other Problems

• There are ensembles also for...
• ...clustering (Vega-Pons and Ruiz-Shulcloper, 2011)
  – trying to unify different clusterings
  – using a consensus function mapping different clusterings to each other
• ...outlier detection (Zimek et al., 2014)
  – unifying outlier scores of different approaches
  – requires score normalization and/or rank aggregation
• etc.
Learning with Costs

- Most classifiers aim at reducing the number of errors
  - all errors are regarded as being equally important

- In reality, misclassification costs may differ

- Consider a warning system in an airplane
  - issue a warning if stall is likely to occur
  - based on a classifier using different sensor data
  - wrong warnings may be ignored by the pilot
  - missing warnings may cause the plane to crash

- Here, we have different costs for
  - actual: true, predicted: false → very expensive
  - actual: false, predicted true → not so expensive

http://i.telegraph.co.uk/multimedia/archive/01419/plane_1419831c.jpg
The MetaCost Algorithm

• Form multiple bootstrap replicates of the training set
  – Learn a classifier on each training set
  – i.e., perform bagging
• Estimate each class’s probability for each example
  – by the fraction of votes that it receives from the ensemble
• Use conditional risk equation to relabel each training example
  – with the estimated optimal class
• Reapply the classifier to the relabeled training set
MetaCost

- Conditional risk $R(i|x)$ is the expected cost of predicting that $x$ belongs to class $i$
  - $R(i|x) = \sum P(j|x)C(i, j)$
  - $C(i, j)$ are the classification costs (classify an example of class $j$ as class $i$)
  - $P(j|x)$ are obtained by running the bagged classifiers

- The goal of MetaCost procedure is: to relabel the training examples with their “optimal” classes
  - i.e., those with lowest risk

- Then, re-run the classifier to build a final model
  - the resulting classifier will be defensive, i.e., make low-risk predictions
  - in the end, the costs are minimized
MetaCost

- Pilot stall alarm example
  - $x_1$: stall, $P(\text{stall}|x_1) = 0.8$
  - $x_2$: no, $P(\text{no}|x_2) = 0.9$
- Risk values:
  - $R(\text{stall}|x_1) = P(\text{stall}|x_1)C(\text{stall},\text{stall}) + P(\text{no}|x_1)C(\text{stall},\text{no}) = 0.2*1 = 0.2$
  - $R(\text{no}|x_1) = P(\text{stall}|x_1)C(\text{no},\text{stall}) + P(\text{no}|x_1)C(\text{no},\text{no}) = 0.8*10 = 8$
  - $R(\text{stall}|x_2) = P(\text{stall}|x_2)C(\text{stall},\text{stall}) + P(\text{no}|x_2)C(\text{stall},\text{no}) = 0.9*1 = 0.9$
  - $R(\text{no}|x_2) = P(\text{stall}|x_2)C(\text{no},\text{stall}) + P(\text{no}|x_2)C(\text{no},\text{no}) = 0.1*10 = 1$
- Since $0.9<1$
  - $x_2$ is relabeled to “stall”

<table>
<thead>
<tr>
<th>actual</th>
<th>predicted</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>stall</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>no stall</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

8/10 classifiers are correct

http://i.telegraph.co.uk/multimedia/archive/01419/plane_1419831c.jpg
MetaCost vs. Balancing

• Recap balancing:
  – in an unbalanced dataset, there is a bias towards the larger class
  – balancing the dataset helps building more meaningful models

• MetaCost:
  – incidentally unbalance the dataset,
    labeling more instances with the “cheap” class
  – make the learner have a bias towards the “cheap” class
    • i.e., expensive mis-classifications are avoided
  – in the end, the overall cost is reduced

• In the example:
  – there will be more false alarms (stall warning, but actually no stall)
  – the risk of not issuing a warning is reduced
MetaCost in RapidMiner

- Hint: use the performance (cost) operator for evaluation
MetaCost in RapidMiner

- Experiment: set misclassification cost
  Rock $\rightarrow$ Mine = 2; Mine $\rightarrow$ Rock = 1

- Non-cost sensitive decision tree:
  - misclassification cost = 0.33

- MetaCost with decision tree:
  - misclassification cost = 0.24
Another Example for Cost-Sensitive Prediction

• Predicting *ordinal* attributes  
  – e.g., very low, low, medium, high, very high

• Typical cost matrix:

<table>
<thead>
<tr>
<th>actual</th>
<th>predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>very low</td>
</tr>
<tr>
<td>very low</td>
<td>0</td>
</tr>
<tr>
<td>low</td>
<td>1</td>
</tr>
<tr>
<td>medium</td>
<td>2</td>
</tr>
<tr>
<td>high</td>
<td>4</td>
</tr>
<tr>
<td>very high</td>
<td>8</td>
</tr>
</tbody>
</table>
Wrap-up

• Ensemble methods in general
  – build a strong model from several weak ones

• Ingredients
  – base learners
  – a combination method

• Variants
  – Voting
  – Bagging (based on sampling)
  – Boosting (based on reweighting instances)
  – Stacking (use learner for combination)

• Also used for cost-sensitive predictions (MetaCost)
Questions?