Data Mining: Classification/Supervised Learning Potpourri

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1 Handling of Continuous Attributes in C4.5. Algorithm

Notation. Let D be a dataset over the list of attributes $A = \{A_1, \ldots, A_n\}$. Let $A_i \in A$ be a **continuous attribute**.

A **binary split** of D on attribute A_i at value α is a pair $D^- \subseteq D$, $D^+ \subseteq D$, such that:

1. $D^- \cup D^+ = D$
2. $D^- \cap D^+ = \emptyset$
3. $(\forall d \in D^-) d[A_i] \leq \alpha$;
4. $(\forall d \in D^+) d[A_i] > \alpha$;

Idea. On each step of **C4.5 Algorithm**, for each continuous attribute A_i find a **binary split** with the best information gain (or information gain ratio). More specifically, the enthropy of a binary split of D on A_i using α is

$$enthropy_{A_i,\alpha}(D) = \frac{|D^-|}{|D|} \cdot enthropy(D^-) + \frac{|D^+|}{|D|} \cdot enthropy(D^+).$$

```
function selectSplittingAttribute(A, D,threshold);  //uses information gain
begin
  p0 := enthropy(D);
  for each  A_i ∈ A do
     if A_i is continuous then
        x := findBestSplit(A_i, D);
        p[A_i] := entropy_{A_i,x}(D);
     else
        p[A_i] := enthropy_{A_i}(D);
     endif
     Gain[A_i] = p0 − p[A_i];   //compute info gain
  endfor
  best := arg(findMax(Gain[]));
  if  Gain[best] >threshold   then return best
  else   return  NULL;
end
```

```
function findBestSplit(A_i, D) //finds best binary split for a continuous attribute
begin
  initialize associative arrays counts_1[], ..., counts_k[];
  initialize associative array Gain;
  p0 := enthropy(D);
  sort D in ascending order on  A_i;
  for l = 1 to |D| do   //Step 1:  scan data
     d := D[l];   // Select next data point from D in order of A_i values
     alpha[l] := d[A_i];   // Remember the l-th split value
     for j = 1 to k do
        if class(d) == c_j then
           counts_j[l] := counts_j[l − 1] + 1;
        else
           counts_j[l] := counts_j[l − 1] + 0;
        endif
     endfor
  endfor
  for l = 1 to |D| do
     //computes entropy of binary split at alpha[l]
     Gain[l] := p0 − entropy(D, A_i, (counts_1[l], ..., counts_k[l]));
  endfor
  best := arg(findMax(Gain[]));
  return  alpha[best];
end
```

Figure 1: A modified version of selectSplittingAttribute() function for the **C4.5 Algorithm**. This version finds the best binary split for any continuous attribute.

The information gain obtained by using A_i with the binary split at α is:

$$Gain_{A_i,\alpha}(D) = enthropy(D) - enthropy_{A_i,\alpha}(D).$$

Finding best binary split. The new version of the selectSplittingAttribute() function is in Figure 1.

- When attribute A_i is **continuous**, new selectSplittingAttribute() calls findBestSplit() function, also shown in Figure 1.
- To find the best binary split, we
  - scan the dataset D and determine the list of all values of A_i.
    Note, that while $dom(A_i)$ is continuous, D contains finitly many distinct values of A_i!
  - For each value x in of A_i from D find $enthropy_{A_i,x}(D)$.
  - Find x with the largest information gain and return it.

Other adjustments to C4.5. One more adjustment to **C4.5** needs to be made.

- if a **categorical attribute** is selected to split D on the current step of the algorithm, this attribute is **removed from the attribute list** passed in the recursive calls to C4.5. (same as before)
- if a **continuous attribute** is selected to split D on the current step of the algorithm, this attribute is **kept in the attribute list** passed in the recursive calls to C4.5. (**new**)

Dealing with "Ghost" Paths

One important adjustment to C4.5 needs to be made to enable it to deal with situations when a subset D_i does not have data point for some value a_j of an attribute A on which D_i is being split.

The version of C4.5. from the previous handout contained this pseudocode:

```
foreach v ∈ dom(A_g) do
  D_v := {t ∈ D|t[A_g] = v};
  if D_v ≠ ∅ then
    T_v := C45(D_v, A − {A_g}, threshold);    //recursive call
  ...
  endif
endfor
```

The if statement in this fragments checks whether the set of data points $t \in D$ for which $t.A = v$, the selected value of the attribute A is empty. The *recursive calls* to C4.5 only happen if it is **not empty**. If $D_v = \emptyset$, no action is taken.

The problem with this approach is that this tree will fail to classify a data point x which has $a.A = v$, and whose other attribute values match the path from the root of the decision tree to the node in question.

```
Algorithm C45(D, A, threshold);
 if for all d ∈ D: class(d) = c_i then
// Step 1:  check termination conditions
    create leaf node r;
    label(r) := c_i;
    T := r;
 else if A = ∅ then
    c := find_most_frequent_label(D);
    create leaf node r;
    label(r) := c;
    T := r;
 else  //Step 2:  select splitting attribute
    A_g := selectSplittingAttribute(A,D, threshold);
    if A_g = NULL then  //no attribute is good for a split
      create leaf node r;
      label(r) := find_most_frequent_label(D);
      T := r;
    else  // Step 3:  Tree Construction
      create tree node r;
      T := r;
      label(r) := A_g;
      foreach v ∈ dom(A_g) do
         D_v := {t ∈ D|t[A_g] = v};
         if D_v ≠ ∅ then
            if A_g is categorical then
              T_v := C45(D_v, A − {A_g}, threshold);   //recursive call
            else   // Ag is numeric
              T_v := C45(D_v, A, threshold);   //recursive call
            endif
            append T_v to r with an edge labeled v;
         else   // Create a "ghost" leaf node
            create leaf node r_v;
            label(r_v) := find_most_frequent_label(D);
            append r_v to r with an edge labeled v;
         endif
      endif
    endif
 endif
 return T;
```

Figure 2: Updated version of th e C4.5 algorithm for decision tree induction. This version handles numeric attribute splits, and creates ”ghost” leaf nodes to ensure that all input data points can be successfully classified.

We can adjust C45 to produce the best possible prediction in such cases by creating a "ghost" leaf node that matches the value v of the attribute A. The classification decision for this leaf node is the **plurality class** of the dataset D.

Figure 2 adjusts the pseudocode accordingly.

C4.5. and Overfitting

Overfitting. Let $D_{training}$ be a training set for a classification problem, and D_{test} be a test set. Let f be a classifier trained on $D_{training}$.

> f ***overfits the data***, *if there exists another classifier* f' *which has* ***lower accuracy*** *than* f *on* $D_{training}$ *but* ***higher accuracy*** *than* f *on* D_{test}.

Casuses of overfitting:

- *Noise in data.* (e.g., wrong class labels)
- *Randomness phenomena.* (training set is not representative of the application domain)
- *Complexity of model.* (too many attributes, some may not be needed for classification)

Dealing with overfitting. Two main approaches:

- **Pre-pruning** or **stopping early**. E.g., the *third termination condition in* **Algorithm C4.5** terminates tree construction early using the user-specified threshold parameter.
- **Post-pruning** or **pruning a constructed tree**. In this approach, the classification algorithm is allowed to *possibly overfit* the data, but a separate **pruning** algorithm will then check the classifier for overfitting.

k-Nearest Neighbors Classification (kNN)

C4.5. and **many other classification techniques** (Neural Nets, SVNs, Rule Induction) are ***eager***: these techniques analyze the training set and construct a classifier *before any test data is read.*

The principle of **lazy evaluation** is to *postpone any data analysis until an actual question has been asked.*

In case of supervised learning, **lazy evaluation** means **not building a classifier** in advance of reading data from the test data set.

k-Nearest Neighbors Classification algorithm (kNN). kNN is a simple, but surprisingly robust **lazy evaluation** algorithm. The idea behind kNN is as follows:

- The input of the algorithm is a training set $D_{training}$, an instance d that needs to be classified and an integer $k > 1$.
- The algorithm computes the *distance* between d and every item $d' \in D$.
- The algorithm selects k **most similar** or **closest** to d records from D: $d_1, \ldots, d_k$, $d_i \in D$.
- The algorithm assigns to d the class of the plurality of items from the list $d_1, \ldots, d_k$.

Distance/similarity measures. The distance (or similarity) between two records can be measured in a number of different ways.

Note: Similarity measures increase as the similarity between two objects increases. **Distance measures** decrease as the similarity between two objects increases.

1. **Eucledian distance**. If D has continuous attributes, each $d \in D$ is essentially a point in N-dimensional space (or an N-dimensional vector). Euclidian distance:

$$d(d_1, d_2) = \sqrt{\sum_{i=1}^{n} (d_1[A_i] - d_2[A_i])^2},$$

   works well in this case.

2. **Manhattan distance**. If D has ordinal, but not necessarily continuous attributes, Manhattan distance may work a bit better:

$$d(d_1, d_2) = \sum_{i}^{n} |d_1[A_i] - d_2[A_i]|.$$

3. **Cosine similarity**. Cosine distance between two vectors is the cosince of the angle between them. Cosine similarity ignores the amplitude of the vectors, and measures only the difference in their *direction*:

$$sim(d_1, d_2) = \cos(d_1, d_2) = \frac{d_1 \cdot d_2}{||d_1|| \cdot ||d_2||} = \frac{\sum_{i=1}^{n} d_1[A_i] \cdot d_2[A_i]}{\sqrt{\sum_{i=1}^{n} d_1[A_i]^2} \cdot \sqrt{\sum_{i=1}^{n} d_2[A_i]^2}}.$$

   If d_1 and d_2 are *colinear* (have the same direction), $sim(d_1, d_2) = 1$. If d_1 and d_2 are *orthogonal*, $sim(d_1, d_2) = 0$.

Ensemble Learning

Bagging

Bagging = Bootstrap **agg**regat**ing**.

Bootstrapping is a statistical technique that one to gather many alternative versions of the single statistic that would ordinarily be calculated from one sample.

Typical bootstrapping scenario. (case resampling) Given a sample D of size n, a **bootstrap sample** of D is a sample of n data items drawn **randomly with replacement** from D.

Note: On average, about 63.2% of items from D will be found in a bootstrapping sample, but some items will be found multiple times.

Bootstrap Aggregating for Supervised Learning. Let D be a training set, $|D| = N$. We construct a **bagging classifier** for D as follows:

Training Stage: Given D, k and a learning algorithm BaseLearner:

1. Create k **bootstrapping replications** $D_1, \ldots, D_k$ of D by using case resampling bootstrapping technique.
2. For each **bootstrapping replication** D_i, create a classifier f_i using the BaseLearner classification method.

Testing Stage: Given $f_1, \ldots, f_k$ and a test record d:

1. Compute $f_1(d), \ldots f_k(d)$.
2. Assign as $class(d)$, the majority (plurality) class among $f_1(d), \ldots, f_k(d)$.

Boosting

Boosting. **Boosting** is a collection of techniques that generate an ensemble of classifiers in a way that each new classifier tries to correct classification errors from the previous stage.

Idea. **Boosting** is applied to a specific classification algorithm called BaseLearner[1].

Each item $d \in D$ is assigned a weight. On first step, $w(d) = \frac{1}{|D|}$. On each step, a classifier f_i is built. Any errors of classification, i.e, items $d \in D$, such that $f(d) \neq class(d)$ are given higher weight.

On the next step, the classication algorithm is made to "pay more attention" to items in D with higher weight.

The final classifier is constructed by weighting the votes of $f_1, \ldots f_k$ by their weighted classification error rate.

AdaBoost. The **Ada**ptive **Boost**ing algorithm [2] (AdaBoost) is shown in Figure 3.

[1] It is also commonly called weak classifier.

```
Algorithm AdaBoost(D, BaseLearner, k) begin
  foreach d_i ∈ D do D_1(i) = 1/|D|;
  for t = 1 to k do    //main loop
     f_t :=BaseLearner(D_t);
     e_t := Σ_{class(d_i)≠f_t(d_i)} D_t(i);
     // f_t is constructed to minimize e_t
     if e_t > 0.5 then    // large error:  redo
        k := k − 1;
        break;
     endif
     a_t := 1/2 ln (1−e_t)/e_t;   //reweighting parameter
     foreach d_i ∈ D do D_{t+1}(i) := D_t(i) · e^{−α_t·class(d_i)·f_t(d_i)};   //reweigh each tuple in D
     Norm_t := Σ_{i=1}^{|D|} D_{t+1}(i);
     foreach d_i ∈ D do D_{t+1}(i) := D_{t+1}(i)/Norm_t;   //normalize new weights
  endfor

f_final(.) := sign(Σ_{t=1}^{k} a_t · f_t(.))
end
```

Figure 3: **AdaBoost**: an adaptive boosting algorithm. This version is for binary category variable $Y = \{-1, +1\}$.

Weak Classifiers. Some classifiers are designed to incorporate the weights of training set elements into consideration. But most, like **C4.5**, do not do so. In order to turn a classifier like **C4.5** into a weak classifier suitable for **AdaBoost**, this classifier can be updated as follows:

- On step t, given the weighted training set D_t, we **sample** D_t to build a training set D'_t. The sampling process uses $D_t(i)$ as the probability of selection of d_i into D'_t on each step.

Voting

When multiple classification algorithms $\mathcal{A}_1, \ldots \mathcal{A}_k$ are available, **direct voting** can be used to combine these classifiers.

Let D be a training set, and $f_1, \ldots f_k$ are the classifiers produced by $\mathcal{A}_1, \ldots, \mathcal{A}_k$ respectively on D. Then the combined classifier f is constructed to return the class label returned by the **plurality** of classifiers $f_1, \ldots f_k$.

Random Forests

Random Forests[1] are an extension of bagging. A bagging technique resamples the training set with replacement, but keeps all attributes in the dataset "active" for each resampled training set.

Random Forests build a collection of decision trees, where each decision tree is built based on a subset of a training set **and** a subset of attributes.

In a nutshell, a Random Forests classifier works as follows:

1. **Input:** Let $D = \{d_1, \ldots, d_n\}$ be the training set, with $class(d_i)$ defined. Let $C = \{c_1, \ldots, c_k\}$ be the class attribute, and let $A = \{A_1, \ldots A_N\}$ be the set of attributes for vectors from D, i.e., given $d \in D$, $d = (x_1, \ldots, x_M)$.

2. **Attribute selection parameter:** A number $m << M$ is fixed throughout the run of a random forest classifier. This number indicates how many attributes is selected to build each decision tree in a forest.

3. **Forest construction:** The classifier builds N decision trees $T_1, \ldots T_N$. Each decision tree is built by selecting a subsample of the training set, and a subset of the attributes.

4. **Single decision tree construction:** Decision tree T_j is built as follows.

   (a) Build a set $D_j \subseteq D$ drawing random k data points from D *with replacement*.

   (b) Select m random attributes $A_1^j, \ldots, A_m^j$ from A *without replacement*.

   (c) Using a decision tree induction procedure (see below), build a decision tree T_j for the training set D_j restricted to attributes $A_1^J, \ldots, A_m^j$. Do not prune the decision trees.

5. **Classification process**: For each data point $d \in D$, (attempt to) classify d by traversing trees $T_1, \ldots, T_N$ to discover classification decisions $c^1, \ldots, c^N$. Choose, as $class(d)$, the most frequently occurring in $c^1, \ldots, c^N$ class.

Caveats. A decision tree T_j may not contain all possible values (paths) for some attribute. This means that some trees won't be able to classify some of the data points in D. The simplest way to deal with this is to ignore. Another way is to follow the description on how to deal with "ghost" paths.

Decision tree induction procedures. Both versions of ID3 (C4.5 without the pruning) and CART, a decision-tree induction algorithm that uses the Gini impurity instead of Information Gain-based measures, can be used.

Gini impurity measure. The Gini impurity measure quantifies how often a randomly chosen *and randomly labelled* data point from a training set will be mislabelled.

Let $D = \{d_1, \ldots, d_n\}$ be a training set.

Let $C = \{c_1, \ldots, c_k\}$ be a class variable.

Let $D_i = \{d \in D | class(d) = c_i\}$ be the set of all training set points from category c_i.

Let $f_i = |D_i|$.

The Gini impurity measure I_G is defined as follows:

$$I_G(D) = \sum_{i=1}^{k} f_i \cdot (1 - f_i) = \sum_{i=1} k f_i - \sum_{i=1} k f_i^2 = 1 - \sum_{i=1} k f_i^2 = \sum_{i \neq j} f_i \cdot f_j.$$

References

[1] Breiman, L. (2001). Random forests. Machine learning, 45(1), 5-32.

[2] Y. Freund, R.E. Shapire. Experiments with a New Boosting Algorithm. In *Proceedings, 13th International Conference on Machine Learning (ICML'96)*, pp. 148–156, 1996.