Evaluating Machine-Learning Methods

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Computer Sciences 760
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Goals for the lecture

you should understand the following concepts

• bias of an estimator
• test sets
• learning curves
• stratified sampling
• cross validation
• confusion matrices
• TP, FP, TN, FN
• ROC curves
• confidence intervals for error
• pairwise t-tests for comparing learning systems
• scatter plots for comparing learning systems
• lesion studies
Bias of an estimator

\[ \theta \] true value of parameter of interest (e.g. model accuracy)
\[ \hat{\theta} \] estimator of parameter of interest (e.g. test set accuracy)

\[ \text{Bias}[\hat{\theta}] = E[\hat{\theta}] - \theta \]

e.g. polling methodologies often have an inherent bias

Test sets revisited

How can we get an unbiased estimate of the accuracy of a learned model?

labeled data set \[ \rightarrow \] training set \[ \rightarrow \] test set

learning method \[ \rightarrow \] learned model \[ \rightarrow \] accuracy estimate
Test sets revisited

How can we get an unbiased estimate of the accuracy of a learned model?

• when learning a model, you should pretend that you don’t have the test data yet (it is “in the mail”)*

• if the test-set labels influence the learned model in any way, accuracy estimates will be biased

* In some applications it is reasonable to assume that you have access to the feature vector (i.e. $x$) but not the $y$ part of each test instance.

Learning curves

How does the accuracy of a learning method change as a function of the training-set size?

This can be assessed by plotting learning curves

Figure from Perluch et al. Journal of Machine Learning Research, 2003
Learning curves

given training/test set partition
  • for each sample size $s$ on learning curve
    • (optionally) repeat $n$ times
      • randomly select $s$ instances from training set
      • learn model
      • evaluate model on test set to determine accuracy $a$
    • plot $(s, a)$ or $(s, \text{avg. accuracy and error bars})$

Limitations of using a single training/test partition

  • we may not have enough data to make sufficiently large training and test sets
    • a larger test set gives us more reliable estimate of accuracy (i.e. a lower variance estimate)
    • but… a larger training set will be more representative of how much data we actually have for learning process

  • a single training set doesn’t tell us how sensitive accuracy is to a particular training sample
Using multiple training/test partitions

- two general approaches for doing this
  - random resampling
  - cross validation

Random resampling

We can address the second issue by repeatedly randomly partitioning the available data into training and set sets.
**Stratified sampling**

When randomly selecting training or validation sets, we may want to ensure that class proportions are maintained in each selected set.

This can be done via stratified sampling: first stratify instances by class, then randomly select instances from each class proportionally.

**Cross validation**

Partition data into \( n \) subsamples.

Iteratively leave one subsample out for the test set, train on the rest.

<table>
<thead>
<tr>
<th>iteration</th>
<th>train on</th>
<th>test on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( S_2 \ S_3 \ S_4 \ S_5 )</td>
<td>( S_1 )</td>
</tr>
<tr>
<td>2</td>
<td>( S_1 \ S_3 \ S_4 \ S_5 )</td>
<td>( S_2 )</td>
</tr>
<tr>
<td>3</td>
<td>( S_1 \ S_2 \ S_4 \ S_5 )</td>
<td>( S_3 )</td>
</tr>
<tr>
<td>4</td>
<td>( S_1 \ S_2 \ S_3 \ S_5 )</td>
<td>( S_4 )</td>
</tr>
<tr>
<td>5</td>
<td>( S_1 \ S_2 \ S_3 \ S_4 )</td>
<td>( S_5 )</td>
</tr>
</tbody>
</table>
Cross validation example

Suppose we have 100 instances, and we want to estimate accuracy with cross validation

<table>
<thead>
<tr>
<th>iteration</th>
<th>train on</th>
<th>test on</th>
<th>correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>s₂ s₃ s₄ s₅</td>
<td>s₁</td>
<td>11 / 20</td>
</tr>
<tr>
<td>2</td>
<td>s₁ s₃ s₄ s₅</td>
<td>s₂</td>
<td>17 / 20</td>
</tr>
<tr>
<td>3</td>
<td>s₁ s₂ s₄ s₅</td>
<td>s₃</td>
<td>16 / 20</td>
</tr>
<tr>
<td>4</td>
<td>s₁ s₂ s₃ s₄</td>
<td>s₅</td>
<td>13 / 20</td>
</tr>
<tr>
<td>5</td>
<td>s₁ s₂ s₃ s₄</td>
<td>s₅</td>
<td>16 / 20</td>
</tr>
</tbody>
</table>

accuracy = 73/100 = 73%

Cross validation

- 10-fold cross validation is common, but smaller values of \( n \) are often used when learning takes a lot of time

- in leave-one-out cross validation, \( n = \# \) instances

- in stratified cross validation, stratified sampling is used when partitioning the data

- CV makes efficient use of the available data for testing

- note that whenever we use multiple training sets, as in CV and random resampling, we are evaluating a learning method as opposed to an individual learned model
Confusion matrices

How can we understand what types of mistakes a learned model makes?

**task: activity recognition from video**

```
Confusion matrix for 2-class problems
```

<table>
<thead>
<tr>
<th></th>
<th>positive</th>
<th>negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>positive</td>
<td>true positives (TP)</td>
<td>false negatives (FN)</td>
</tr>
<tr>
<td>negative</td>
<td>false positives (FP)</td>
<td>true negatives (TN)</td>
</tr>
</tbody>
</table>

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

\[
\text{error} = 1 - \text{accuracy} = \frac{FP + FN}{TP + FP + FN + TN}
\]
Is accuracy an adequate measure of predictive performance?

Accuracy may not be useful measure in cases where:

- There is a large class skew
  - Is 98% accuracy good when 97% of the instances are negative?

- There are differential misclassification costs – say, getting a positive wrong costs more than getting a negative wrong
  - Consider a medical domain in which a false positive results in an extraneous test but a false negative results in a failure to treat a disease

- We are most interested in a subset of high-confidence predictions

Other accuracy metrics

<table>
<thead>
<tr>
<th>Actual Class</th>
<th>Predicted Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>true positives (TP)</td>
</tr>
<tr>
<td>Negative</td>
<td>false negatives (FN)</td>
</tr>
</tbody>
</table>

- True positive rate (recall) = \( \frac{TP}{TP + FN} \)
- False positive rate = \( \frac{FP}{TN + FP} \)
ROC curves

A Receiver Operating Characteristic (ROC) curve plots the TP-rate vs. the FP-rate as a threshold on the confidence of an instance being positive is varied.

Different methods can work better in different parts of ROC space.

Algorithm for creating an ROC curve

let \( \{(y^{(1)}, c^{(1)}) , \ldots, (y^{(m)}, c^{(m)})\} \) be the test-set instances sorted according to predicted confidence

let \( \text{num\_neg}, \text{num\_pos} \) be the number of negative/positive instances in the test set

\( TP = 0, \ FP = 0 \)

\( last\_TP = 0 \)

for \( i = 1 \) to \( m \)

// find thresholds where there is a pos instance on high side, neg instance on low side
if \( (c^{(i)} \neq c^{(i-1)}) \) and \( (y^{(i)} == \text{neg}) \) and \( (TP > last\_TP) \)

\[ FPR = FP / \text{num\_neg}, \ TPR = TP / \text{num\_pos} \]

output \((FPR, TPR)\) coordinate

\( last\_TP = TP \)

if \( y^{(i)} == \text{pos} \)

++TP

else

++FP

\[ FPR = FP / \text{num\_neg}, \ TPR = TP / \text{num\_pos} \]

output \((FPR, TPR)\) coordinate
Plotting an ROC curve

<table>
<thead>
<tr>
<th>instance</th>
<th>confidence positive</th>
<th>correct class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex 9</td>
<td>.99</td>
<td>+</td>
</tr>
<tr>
<td>Ex 7</td>
<td>.98 TPR= 2/5, FPR= 0/5</td>
<td>+</td>
</tr>
<tr>
<td>Ex 1</td>
<td>.72</td>
<td>-</td>
</tr>
<tr>
<td>Ex 2</td>
<td>.70</td>
<td>+</td>
</tr>
<tr>
<td>Ex 6</td>
<td>.65 TPR= 4/5, FPR= 1/5</td>
<td>+</td>
</tr>
<tr>
<td>Ex 10</td>
<td>.51</td>
<td>-</td>
</tr>
<tr>
<td>Ex 3</td>
<td>.39</td>
<td>-</td>
</tr>
<tr>
<td>Ex 5</td>
<td>.24 TPR= 5/5, FPR= 3/5</td>
<td>+</td>
</tr>
<tr>
<td>Ex 4</td>
<td>.11</td>
<td>-</td>
</tr>
<tr>
<td>Ex 8</td>
<td>.01 TPR= 5/5, FPR= 5/5</td>
<td>-</td>
</tr>
</tbody>
</table>

ROC curve example

Task: recognizing genomic units called operons

figure from Bockhorst et al., Bioinformatics 2003
ROC curves and misclassification costs

The best operating point depends on the relative costs of FN and FP misclassifications.

ROC curves

Does a low false-positive rate indicate that most positive predictions (i.e. predictions with confidence > some threshold) are correct?

suppose our TPR is 0.9, and FPR is 0.01

<table>
<thead>
<tr>
<th>fraction of instances that are positive</th>
<th>fraction of positive predictions that are correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.989</td>
</tr>
<tr>
<td>0.1</td>
<td>0.909</td>
</tr>
<tr>
<td>0.01</td>
<td>0.476</td>
</tr>
<tr>
<td>0.001</td>
<td>0.083</td>
</tr>
</tbody>
</table>
Other accuracy metrics

true positives (TP)  false positives (FP)
false negatives (FN)  true negatives (TN)

\[
\text{recall (TP rate)} = \frac{TP}{\text{actual pos}} = \frac{TP}{TP + FN}
\]

\[
\text{precision (positive predictive value)} = \frac{TP}{\text{predicted pos}} = \frac{TP}{TP + FP}
\]

Precision/recall curves

A precision/recall curve plots the precision vs. recall (TP-rate) as a threshold on the confidence of an instance being positive is varied.
Precision/recall curve example

How do we get one ROC/PR curve when we do cross validation?

Approach 1
- make assumption that confidence values are comparable across folds
- pool predictions from all test sets
- plot the curve from the pooled predictions

Approach 2 (for ROC curves)
- plot individual curves for all test sets
- view each curve as a function
- plot the average curve for this set of functions
Comments on ROC and PR curves

both
- allow predictive performance to be assessed at various levels of confidence
- assume binary classification tasks
- sometimes summarized by calculating \textit{area under the curve}

ROC curves
- insensitive to changes in class distribution (ROC curve does not change if the proportion of positive and negative instances in the test set are varied)
- can identify optimal classification thresholds for tasks with differential misclassification costs

precision/recall curves
- show the fraction of predictions that are false positives
- well suited for tasks with lots of negative instances

Confidence intervals on error

Given the observed error (accuracy) of a model over a limited sample of data, how well does this error characterize its accuracy over additional instances?

Suppose we have
- a learned model \( h \)
- a test set \( S \) containing \( n \) instances drawn independently of one another and independent of \( h \)
- \( n \geq 30 \)
- \( h \) makes \( r \) errors over the \( n \) instances

our best estimate of the error of \( h \) is

\[
\text{error}_S(h) = \frac{r}{n}
\]
Confidence intervals on error

With approximately $C\%$ probability, the true error lies in the interval

$$error_r(h) \pm z_C \sqrt{\frac{error_r(h)(1-error_r(h))}{n}}$$

where $z_C$ is a constant that depends on $C$ (e.g. for 95% confidence, $z_C = 1.96$)

Confidence intervals on error

How did we get this?

1. Our estimate of the error follows a binomial distribution given by $n$ and $p$ (the true error rate over the data distribution)

2. Most common way to determine a binomial confidence interval is to use the normal approximation (although can calculate exact intervals if $n$ is not too large)
Confidence intervals on error

2. When \( n \geq 30 \), and \( p \) is not too extreme, the normal distribution is a good approximation to the binomial

3. We can determine the \( C\% \) confidence interval by determining what bounds contain \( C\% \) of the probability mass under the normal distribution

Comparing learning systems

How can we determine if one learning system provides better performance than another
- for a particular task?
- across a set of tasks / data sets?
Motivating example

<table>
<thead>
<tr>
<th>System A:</th>
<th>80%</th>
<th>50</th>
<th>75</th>
<th>...</th>
<th>99</th>
</tr>
</thead>
<tbody>
<tr>
<td>System B:</td>
<td>79</td>
<td>49</td>
<td>74</td>
<td>...</td>
<td>98</td>
</tr>
<tr>
<td>$\delta$:</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>...</td>
<td>+1</td>
</tr>
</tbody>
</table>

- Mean accuracy for System A is better, but the standard deviations for the two clearly overlap
- Notice that System A is always better than System B

Comparing systems using a paired $t$ test

- consider $\delta$'s as observed values of a set of i.i.d. random variables

- null hypothesis: the 2 learning systems have the same accuracy
- alternative hypothesis: one of the systems is more accurate than the other

- hypothesis test:
  - use paired $t$-test do determine probability $p$ that mean of $\delta$'s would arise from null hypothesis
  - if $p$ is sufficiently small (typically $< 0.05$) then reject the null hypothesis
Comparing systems using a paired $t$ test

1. calculate the sample mean
   \[ \bar{\delta} = \frac{1}{n} \sum_{i=1}^{n} \delta_i \]

2. calculate the $t$ statistic
   \[ t = \frac{\bar{\delta}}{\sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (\delta_i - \bar{\delta})^2}} \]

3. determine the corresponding $p$-value, by looking up $t$ in a table of values for the Student's $t$-distribution with $n-1$ degrees of freedom

The null distribution of our $t$ statistic looks like this.

The $p$-value indicates how far out in a tail our $t$ statistic is.

If the $p$-value is sufficiently small, we reject the null hypothesis, since it is unlikely we'd get such a $t$ by chance.

For a two-tailed test, the $p$-value represents the probability mass in these two regions.
Why do we use a two-tailed test?

- A two-tailed test asks the question: is the accuracy of the two systems different.
- A one-tailed test asks the question: is system A better than system B.
- A priori, we don’t know which learning system will be more accurate (if there is a difference) – we want to allow that either one might be.

Comments on hypothesis testing to compare learning systems

- The paired $t$-test can be used to compare two learning systems.
- Other tests (e.g. McNemar’s $\chi^2$ test) can be used to compare two learned models.
- A statistically significant difference is not necessarily a large-magnitude difference.
Scatter plots for pairwise method comparison

We can compare the performance of two methods $A$ and $B$ by plotting $(A$ performance, $B$ performance) across numerous data sets.

Lesion studies

We can gain insight into what contributes to a learning system's performance by removing (lesioning) components of it.

The ROC curves here show how performance is affected when various feature types are removed from the learning representation.
To avoid pitfalls, ask

1. Is my held-aside test data really representative of going out to collect new data?
   • Even if your methodology is fine, someone may have collected features for positive examples differently than for negatives – should be randomized
   • Example: samples from cancer processed by different people or on different days than samples for normal controls

To avoid pitfalls, ask

2. Did I repeat my entire data processing procedure on every fold of cross-validation, using only the training data for that fold?
   • On each fold of cross-validation, did I ever access in any way the label of a test instance?
   • Any preprocessing done over entire data set (feature selection, parameter tuning, threshold selection) must not use labels
To avoid pitfalls, ask

3. Have I modified my algorithm so many times, or tried so many approaches, on this same data set that I (the human) am overfitting it?

- Have I continually modified my preprocessing or learning algorithm until I got some improvement on this data set?
- If so, I really need to get some additional data now to at least test on