Machine Learning

Topic 7: Boosting
(based on Rob Schapire’s IJCAI’99 talk)
Horse Race Prediction
How to Make $$$ In Horse Races?

• Ask a professional.

• Suppose:
  – Professional cannot give single highly accurate rule
  – …but presented with a set of races, can always generate better-than-random rules

• Can you get rich?
Idea

1) Ask expert for rule-of-thumb
2) Assemble set of cases where rule-of-thumb fails (hard cases)
3) Ask expert for a rule-of-thumb to deal with the hard cases
4) Goto Step 2

- Combine all rules-of-thumb
- Expert could be “weak” learning algorithm
Questions

• **How to choose** races on each round?
  – concentrate on “hardest” races
    (those most often misclassified by previous rules of thumb)

• **How to combine** rules of thumb into single prediction rule?
  – take (weighted) majority vote of rules of thumb
Boosting

• **boosting** = general method of converting rough rules of thumb into highly accurate prediction rule

• more technically:
  – given “weak” learning algorithm that can consistently find hypothesis (classifier) with error \( \leq \frac{1}{2} - \gamma \) (implicit here is that \( \gamma \leq \frac{1}{2} \))

  – a boosting algorithm can provably construct single hypothesis with error \( \leq \varepsilon \)
This Lecture

• Introduction to boosting (AdaBoost)
• Analysis of training error
• Analysis of generalization error based on theory of margins
• Extensions
• Experiments
A Formal View of Boosting

• Given training set \( X = \{(x_1, y_1), \ldots, (x_m, y_m)\} \)
• \( y \in \{+1, -1\} \) is the correct label of \( x_i \in X \)
• for timesteps \( t = 1, \ldots, T \):
  • construct a distribution \( D_t \) on \( \{1, \ldots, m\} \)
  • Find a weak hypothesis \( h_t : X \rightarrow \{+1, -1\} \)
    with small error on \( D_t \):
      \[ \varepsilon_t = \Pr_{D_t}[h_t(x_i) \neq y_i] \]
  • Output a final hypothesis \( H_{\text{final}} \) that combines the weak hypotheses in a good way

HOW?
Weighting the Votes

• $H_{\text{final}}$ is a weighted combination of the choices from all our hypotheses.

\[
H_{\text{final}}(x) = \text{sgn}\left( \sum_t \alpha_t h_t(x) \right)
\]
The Hypothesis Weight

- $\alpha_t$ determines how “seriously” we take this particular classifier’s answer

$$\alpha_t = \frac{1}{2} \ln \left( \frac{1 - \mathcal{E}_t}{\mathcal{E}_t} \right)$$

The error on training distribution $D_t$
The Training Distribution

- $D_t$ determines which elements in the training set we focus on.

\[
D_1(i) = \frac{1}{m}
\]

\[
D_{t+1}(i) = \frac{D_t(i)}{Z_t} \cdot \begin{cases} 
  e^{-\alpha_t} & \text{if } y_i = h_t(x_i) \\
  e^{\alpha_t} & \text{if } y_i \neq h_t(x_i)
\end{cases}
\]

Size of the training set

The right answer

What we guessed

Normalization factor

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The Hypothesis Weight

\[ \alpha_t = \frac{1}{2} \ln \left( \frac{1 - \varepsilon_t}{\varepsilon_t} \right) > 0 \]

\[ D_{t+1} = \frac{D_t}{Z_t} \cdot \begin{cases} e^{-\alpha_t} & \text{if } y_i = h_t(x_i) \\ e^{\alpha_t} & \text{if } y_i \neq h_t(x_i) \end{cases} \]
AdaBoost [Freund&Schapire ’97]

• constructing $D_t$:
  • $D_1(i) = \frac{1}{m}$
  • given $D_t$ and $h_t$:
    $$D_{t+1} = \frac{D_t}{Z_t} \cdot \begin{cases} e^{-\alpha_t} & \text{if } y_i = h_t(x_i) \\ e^{\alpha_t} & \text{if } y_i \neq h_t(x_i) \end{cases}$$
    $$= \frac{D_t}{Z_t} \cdot \exp(-\alpha_t \cdot y_i \cdot h_t(x_i))$$

  where: $Z_t =$ normalization constant
  $$\alpha_t = \frac{1}{2} \ln \left( \frac{1-\varepsilon_t}{\varepsilon_t} \right) > 0$$

• final hypothesis: $H_{\text{final}}(x) = \text{sgn} \left( \sum_t \alpha_t h_t(x) \right)$
A Formal View of Boosting

- Given **training set** $X = \{(x_1, y_1), \ldots, (x_m, y_m)\}$
- $y \in \{+1, -1\}$ is the correct label of $x_i \in X$
- for timesteps $t = 1, \ldots, T$:
  - construct a distribution $D_t$ on $\{1, \ldots, m\}$
  - Find a **weak hypothesis** $h_t : X \rightarrow \{+1, -1\}$ with small error on $D_t$: $\varepsilon_t = \Pr_{D_t}[h_t(x_i) \neq y_i]$

- Output a **final hypothesis** $H_{\text{final}}$ that combines the weak hypotheses in a good way
Toy Example

$D_1$

[Diagram of a toy example with positive (+) and negative (−) symbols distributed in a quadrant.]
Round 1

\[ h_1 \]

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

\[ D_2 \]

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Round 2

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

$\varepsilon_3 = 0.14$

$\alpha_3 = 0.92$
\[ H_{\text{final}} = \text{sign}(0.42 + 0.65 + 0.92) \]
Analyzing the Training Error

• Theorem [Freund&Schapire ’97]:
  write $\varepsilon_t$ as $\frac{1}{2} - \gamma_t$
  then, training error($H_{\text{final}}$) $\leq \exp\left(-2\sum_t \gamma_t^2\right)$
  so if $\forall t$: $\gamma_t \geq \gamma \geq 0$
  then, training error($H_{\text{final}}$) $\leq e^{-2\gamma^2T}$
Analyzing the Training Error

So what? This means **AdaBoost** is **adaptive**: does not need to know $\gamma$ or $T$ **a priori**

can exploit $\gamma_t \gg \gamma$

•...as long as $\frac{1}{2} > \gamma$
Proof Intuition

• on round $t$:
  increase weight of examples incorrectly classified by $h_t$

• if $x_i$ incorrectly classified by $H_{\text{final}}$
  then $x_i$ incorrectly classified by weighted majority of $h_t$’s
  then $x_i$ must have “large” weight under final dist. $D_{T+1}$

• since total weight $\leq 1$:
  number of incorrectly classified examples “small”
Analyzing Generalization Error

we expect:

- training error to continue to drop (or reach zero)
- test error to increase when $H_{\text{final}}$ becomes “too complex” (Occam’s razor)
A Typical Run

- Test error does not increase even after 1,000 rounds (~2,000,000 nodes)
- Test error continues to drop after training error is zero!
- Occam’s razor wrongly predicts “simpler” rule is better.

(Boosting on C4.5 on “letter” dataset)
A Better Story: Margins

Key idea: Consider confidence (margin):

- with
  \[ H_{final}(x) = \text{sgn}(f(x)) \quad f(x) = \frac{\sum_t \alpha_t h_t(x)}{\sum_t \alpha_t} \in [-1,1] \]

- define: margin of \((x,y) = y \cdot f(x)\)
Margins for Toy Example

\[ f = \begin{pmatrix} 0.42 \\ +0.65 \\ +0.92 \end{pmatrix} \]

\[ f(0.42 + 0.65 + 0.92) \]
The Margin Distribution

<table>
<thead>
<tr>
<th>epoch</th>
<th>5</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>training error</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>test error</td>
<td>8.4</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>%margins ≤ 0.5</td>
<td>7.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Minimum margin</td>
<td>0.14</td>
<td>0.52</td>
<td>0.55</td>
</tr>
</tbody>
</table>
Boosting Maximizes Margins

• Can be shown to minimize

\[ \sum_i e^{-y_i f(x_i)} = \sum_i e^{-y_i \sum_t \alpha_t h_t(x_i)} \propto \text{to margin of } (x_i, y_i) \]
Analyzing Boosting Using Margins

generalization error bounded by function of training sample margins:

\[
\text{error} \leq \hat{\Pr}[\text{margin}_f(x, y) \leq \theta] + \tilde{O}\left(\sqrt{\text{VC}(H)} m\theta^2\right)
\]

- larger margin \(\Rightarrow\) better bound
- bound independent on \# of epochs
- boosting tends to increase margins of training examples by concentrating on those with smallest margin
Relation to SVMs

SVM: map $x$ into high-dim space, separate data linearly
Relation to SVMs (cont.)

\[ H(x) = \begin{cases} 
+1 & \text{if } 2x^5 - 5x^2 + x > 10 \\
-1 & \text{otherwise}
\end{cases} \]

\[ \tilde{h}(x) = (1, x, x^2, x^3, x^4, x^5) \]

\[ \tilde{\alpha} = (-10, 1, -5, 0, 0, 2) \]

\[ H(x) = \begin{cases} 
+1 & \text{if } \tilde{\alpha} \cdot \tilde{h}(x) > 0 \\
-1 & \text{otherwise}
\end{cases} \]
Relation to SVMs

- Both maximize margins:

\[ \theta = \max_w \min_i \frac{(\vec{\alpha} \cdot \vec{h}(x_i))y_i}{\|\vec{\alpha}\|} \]

- SVM: \( \|\vec{\alpha}\|_2 \) Euclidean norm \((L_2)\)
- AdaBoost: \( \|\vec{\alpha}\|_1 \) Manhattan norm \((L_1)\)

- Has implications for optimization, PAC bounds

See [Freund et al ‘98] for details
Extensions: Multiclass Problems

• Reduce to binary problem by creating several binary questions for each example:

  • “does or does not example $x$ belong to class 1?”
  • “does or does not example $x$ belong to class 2?”
  • “does or does not example $x$ belong to class 3?”

  • 
  • 
  • 

Extensions: Confidences and Probabilities

• Prediction of hypothesis $h_t$: $\text{sgn}(h_t(x))$

• Confidence of hypothesis $h_t$: $|h_t(x)|$

• Probability of $H_{\text{final}}$: $\Pr_f[y = +1 | x] = \frac{e^{f(x)}}{e^{f(x)} + e^{-f(x)}}$

[Schapire&Singer ‘98], [Friedman, Hastie & Tibshirani ‘98]
Practical Advantages of AdaBoost

• (quite) fast
• simple + easy to program
• only a single parameter to tune ($T$)
• no prior knowledge
• flexible: can be combined with any classifier (neural net, C4.5, ...)
• provably effective (assuming weak learner)
  • shift in mind set: goal now is merely to find hypotheses that are better than random guessing
• finds outliers
Caveats

• performance depends on data & weak learner
• AdaBoost can fail if
  – weak hypothesis too complex (overfitting)
  – weak hypothesis too weak ($\gamma_t \to 0$ too quickly),
    • underfitting
    • Low margins $\to$ overfitting
• empirically, AdaBoost seems especially susceptible to noise
UCI Benchmarks

Comparison with

- C4.5 (Quinlan’s Decision Tree Algorithm)
- Decision Stumps (only single attribute)
Text Categorization

database: Reuters
Conclusion

- boosting useful tool for classification problems
  - grounded in rich theory
  - performs well experimentally
  - often (but not always) resistant to overfitting
  - many applications

- but
  - slower classifiers
  - result less comprehensible
  - sometime susceptible to noise
Background

• [Valiant’ 84]
  introduced theoretical PAC model for studying machine learning

• [Kearns&Valiant’ 88]
  open problem of finding a boosting algorithm

• [Schapire’ 89], [Freund’ 90]
  first polynomial-time boosting algorithms

• [Drucker, Schapire&Simard ’ 92]
  first experiments using boosting
• [Freund&Schapire ’95]
  – introduced AdaBoost algorithm
  – strong practical advantages over previous boosting algorithms

• experiments using AdaBoost:
  [Drucker&Cortes ’95] [Schapire&Singer ’98]
  [Jackson&Cravon ’96] [Maclin&Opitz ’97]
  [Freund&Schapire ’96] [Bauer&Kohavi ’97]
  [Quinlan ’96] [Schwenk&Bengio ’98]
  [Breiman ’96][]Dietterich’98]

• continuing development of theory & algorithms:
  [Schapire,Freund,Bartlett&Lee ’97] [Schapire&Singer ’98]
  [Breiman ’97] [Mason, Bartlett&Baxter ’98]
  [Grive and Schuurmans’98] [Friedman, Hastie&Tibshirani ’98]