AdaBoost

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The algorithm

The input training data is $\{(x_i, y_i)\}_{i=1}^n$ from $\mathcal{X} \times \{-1, +1\}$.

- Initialize $D_1(i) := 1/n$ for each $i = 1, \dots, n$.
- For $t = 1, \dots, T$, do:
  - Give D_t-weighted examples to Weak Learner; get back $h_t \colon \mathcal{X} \to \{-1, +1\}$.
  - Compute weight on h_t and update weights on examples:

$$\begin{aligned} s_t &:= \sum_{i=1}^n D_t(i) \cdot y_i h_t(x_i) \\ \alpha_t &:= \frac{1}{2} \ln \frac{1 + s_t}{1 - s_t} \\ D_{t+1}(i) &:= \frac{D_t(i) \cdot \exp(-\alpha_t \cdot y_i h_t(x_i))}{Z_t} \quad \text{for each } i = 1, \dots, n \end{aligned}$$

    where

$$Z_t := \sum_{i=1}^n D_t(i) \cdot \exp(-\alpha_t \cdot y_i h_t(x_i))$$

    is the normalizer that makes D_{t+1} a probability distribution.

- Final hypothesis is $\hat{h}$ defined by $\hat{h}(x) := \operatorname{sign}\left(\sum_{t=1}^T \alpha_t \cdot h_t(x)\right)$ for $x \in \mathcal{X}$.

Training error rate bound

Let $\hat{\ell}$ be the function defined by

$$\hat{\ell}(x) := \sum_{t=1}^T \alpha_t \cdot h_t(x) \quad \text{for } x \in \mathcal{X}$$

so $\hat{h}(x) = \operatorname{sign}(\hat{\ell}(x))$. The training error rate of $\hat{h}$ can be bounded above by the average exponential loss of $\hat{\ell}$:

$$\frac{1}{n} \sum_{i=1}^n \mathbf{1}\{\hat{h}(x_i) \neq y_i\} \leq \frac{1}{n} \sum_{i=1}^n \exp(-y_i \hat{\ell}(x_i)).$$

This holds because

$$\hat{h}(x_i) \neq y_i \Leftrightarrow -y_i \hat{\ell}(x_i) \geq 0 \Leftrightarrow \exp(-y_i \hat{\ell}(x_i)) \geq 1.$$

Furthermore, the average exponential loss of $\hat{\ell}$ equals the product of the normalizers from all rounds:

$$\begin{aligned}
\frac{1}{n}\sum_{i=1}^{n}\exp(-y_i\hat{\ell}(x_i)) &= \sum_{i=1}^{n} D_1(i)\cdot\exp\left(-\sum_{t=1}^{T}\alpha_t\cdot y_ih_t(x_i)\right) \\
&= Z_1\sum_{i=1}^{n}\frac{D_1(i)\cdot\exp(-\alpha_1\cdot y_ih_1(x_i))}{Z_1}\cdot\exp\left(-\sum_{t=2}^{T}\alpha_t\cdot y_ih_t(x_i)\right) \\
&= Z_1\sum_{i=1}^{n}D_2(i)\cdot\exp\left(-\sum_{t=2}^{T}\alpha_t\cdot y_ih_t(x_i)\right) \\
&= Z_1Z_2\sum_{i=1}^{n}\frac{D_2(i)\cdot\exp(-\alpha_2\cdot y_ih_2(x_i))}{Z_2}\cdot\exp\left(-\sum_{t=3}^{T}\alpha_t\cdot y_ih_t(x_i)\right) \\
&= Z_1Z_2Z_3\sum_{i=1}^{n}D_3(i)\cdot\exp\left(-\sum_{t=3}^{T}\alpha_t\cdot y_ih_t(x_i)\right) \\
&= \cdots \\
&= \prod_{t=1}^{T}Z_t.
\end{aligned}$$

Since each $y_ih_t(x_i)\in\{-1,+1\}$, the normalizer Z_t can be written as

$$\begin{aligned}
Z_t &= \sum_{i=1}^{n}D_t(i)\cdot\exp(-\alpha_t\cdot y_ih_t(x_i)) \\
&= \sum_{i=1}^{n}D_t(i)\cdot\left(\frac{1+y_ih_t(x_i)}{2}\exp(-\alpha_t)+\frac{1-y_ih_t(x_i)}{2}\exp(\alpha_t)\right) \\
&= \sum_{i=1}^{n}D_t(i)\cdot\left(\frac{1+y_ih_t(x_i)}{2}\sqrt{\frac{1-s_t}{1+s_t}}+\frac{1-y_ih_t(x_i)}{2}\sqrt{\frac{1+s_t}{1-s_t}}\right) \\
&= \sqrt{(1+s_t)(1-s_t)} \\
&= \sqrt{1-s_t^2}.
\end{aligned}$$

So, we conclude the following bound on the training error rate of $\hat{h}$:

$$\frac{1}{n}\sum_{i=1}^{n}\mathbf{1}\{\hat{h}(x_i)\neq y_i\}\leq\frac{1}{n}\sum_{i=1}^{n}\exp(-y_i\hat{\ell}(x_i))=\prod_{t=1}^{T}Z_t=\prod_{t=1}^{T}\sqrt{1-s_t^2}\leq\exp\left(-\frac{1}{2}\sum_{t=1}^{T}s_t^2\right)$$

where the last step uses the fact that $1+x\leq e^x$ for any real number x.

(The bound is usually written in terms of $\gamma_t := s_t/2$, i.e., as $\exp(-2\sum_{t=1}^{T}\gamma_t^2)$.)

Margins on training examples

Let $\hat{g}$ be the function defined by

$$\hat{g}(x) := \frac{\sum_{t=1}^{T}\alpha_t\cdot h_t(x)}{\sum_{t=1}^{T}|\alpha_t|}\quad\text{for } x\in\mathcal{X}$$

so $y_i\hat{g}(x_i)$ is the margin achieved on example (x_i,y_i). We may assume without loss of generality that $\alpha_t\geq 0$ for each $t=1,\ldots,T$ (by replacing h_t with $-h_t$ as needed.) Fix a value $\theta\in(0,1)$, and consider the fraction of training examples on which $\hat{g}$ achieves a margin at most θ:

$$\frac{1}{n}\sum_{i=1}^{n}\mathbf{1}\{y_i\hat{g}(x_i) \le \theta\}.$$

This quantity can be bounded above using the arguments from before:

$$\begin{aligned}
\frac{1}{n}\sum_{i=1}^{n}\mathbf{1}\{y_i\hat{g}(x_i) \le \theta\} &= \frac{1}{n}\sum_{i=1}^{n}\mathbf{1}\left\{y_i\hat{\ell}(x_i) \le \theta\sum_{t=1}^{T}\alpha_t\right\} \\
&\le \exp\left(\theta\sum_{t=1}^{T}\alpha_t\right)\cdot\frac{1}{n}\sum_{i=1}^{n}\exp(-y_i\hat{\ell}(x_i)) \\
&= \exp\left(\theta\sum_{t=1}^{T}\alpha_t\right)\cdot\prod_{t=1}^{T}\sqrt{1-s_t^2} \\
&= \prod_{t=1}^{T}\sqrt{(1+s_t)^{1+\theta}(1-s_t)^{1-\theta}}.
\end{aligned}$$

Suppose that for some $\gamma > 0$, $s_t \ge 2\gamma$ for all $t = 1, \ldots, T$. If $\theta < \gamma$, then using calculus, it can be shown that each term in the product is less than 1:

$$\sqrt{(1+s_t)^{1+\theta}(1-s_t)^{1-\theta}} < 1.$$

Hence, the bound decreases to zero exponentially fast with T.