Machine Learning Theory 2025
Lecture 12

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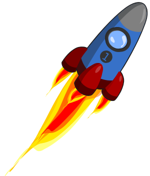
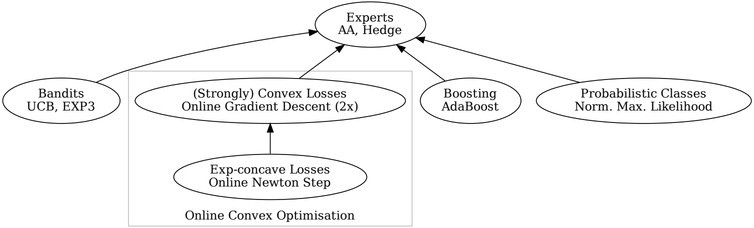
- Boosting:
  - Weak and strong PAC learning
  - Boosting by Online Learning
  - AdaBoost algorithm
  - Analysis
  - VC dimension results



Recap

Overview of Second Half of Course



Material: course notes on MLT website.

Outlook

Today: application of **online learning** to good effect in **statistical learning**

Main point: Boosting gets the training error down (to 0).

With: Bound on VC dimension
Get: PAC learning guarantee

Weak Learning

Weak Learning

Consider a hypothesis class $\mathcal{H} \subseteq \{\pm 1\}^{\mathcal{X}}$ for binary classification.
$\mathcal{D}$ is **$\mathcal{H}$-realisable** if there is $h \in \mathcal{H}$ such that $\mathbb{P}_{X,Y \sim \mathcal{D}}[h(X) = Y] = 1$.

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Definition (Strong Learnability)

Algorithm $\mathcal{A}$ **PAC learns** $\mathcal{H}$ with sample complexity $m_{\mathcal{H}} : (0,1)^2 \to \mathbb{N}$ if for any $\mathcal{H}$-realisable $\mathcal{D}$, any $(\epsilon, \delta) \in (0,1)^2$ and any $m \geq m_{\mathcal{H}}(\epsilon, \delta)$

$$\underset{S^m \overset{\text{iid}}{\sim} \mathcal{D}}{\mathbb{P}} \left\{ L_{\mathcal{D}}(h_{\mathcal{A},S}) \leq \epsilon \qquad \right\} \geq 1 - \delta.$$

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Definition (γ-Weak Learnability, for $\gamma \in (0, 1/2)$)

Algorithm $\mathcal{A}$ **γ-weakly learns** $\mathcal{H}$ with sample complexity $m_{\mathcal{H}} : (0,1) \to \mathbb{N}$ if for any $\mathcal{H}$-realisable $\mathcal{D}$, any $\delta \in (0,1)$ and any $m \geq m_{\mathcal{H}}(\delta)$

$$\mathbb{P}_{S^m \overset{\text{iid}}{\sim} \mathcal{D}} \left\{ L_{\mathcal{D}}(h_{\mathcal{A},S}) \leq \frac{1}{2} - \gamma \right\} \geq 1 - \delta.$$

Question

Is a weakly learnable class always PAC learnable?

- If NO $\Rightarrow$ perhaps should focus on weak learnability?
- If YES $\Rightarrow$ how? efficiency?

What we know

Proposition

$\mathcal{H}$ is PAC learnable iff it is weak learnable.

Proof.

- If $\text{VCdim}(\mathcal{H}) < \infty$ then $\mathcal{H}$ is PAC learnable and hence weak learnable.
- If $\text{VCdim}(\mathcal{H}) = \infty$, then by the Fundamental Theorem the sample complexity at (ϵ, δ) is at least of order

$$\geq \frac{\text{VCdim}(\mathcal{H}) + \ln \frac{1}{\delta}}{\epsilon}$$

which is infinite even for $\epsilon = \frac{1}{2} - \gamma$.

□

What we know

Idea: perhaps ERM for $\mathcal{B} \subseteq \mathcal{H}$ is a weak learner for $\mathcal{H}$.
Can we **boost** an **efficient** weak learner for $\mathcal{H}$ to an **efficient** strong learner for $\mathcal{H}$?

Example

Consider instance space $\mathcal{X} = \mathbb{R}$. Say

$$\mathcal{H} \;=\; \{\text{Three-piece classifiers}\}$$

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As $\mathrm{VCdim}(\mathcal{B}) = 2$, we can agnostic(!) PAC learn $\mathcal{B}$ to accuracy $\epsilon = \frac{1}{12}$ with sample size of order $\epsilon^{-2} \ln \frac{1}{\delta}$. E.g. by ERM.

With probability $1 - \delta$, get

$$L_{\mathcal{D}}(h_S) \;\leq\; L_{\mathcal{D}}(f^*_{\mathcal{B}}) + \frac{1}{12} \;\leq\; \frac{1}{3} + \frac{1}{12} \;=\; \frac{1}{2} - \frac{1}{12}$$

So we can γ-weak learn $\mathcal{H}$ for $\gamma = \frac{1}{12}$.

Boosting

Boosting Cartoon

Start with sample $S = (x_i, y_i)_{i=1}^m$.

Maintain a hypothesis f_t. In round t,

- Create distribution $\mathcal{D}_t$ reweighting S
  Put more weight on examples misclassified by f_t
- Ask Weak Learner for new hypothesis h_t making $\leq 1/2 - \gamma$ mistakes on $\mathcal{D}_t$.
  So h_t gets right what f_t gets wrong
- Obtain improved f_{t+1} by incorporating h_t into f_t.

Weak learning interface

Learning Theory Perspective

A weak learner takes a **sample** from $\mathcal{D}$ and outputs an $(\frac{1}{2} - \gamma)$-good hypothesis **w.p.** $1 - \delta$.

Need to account for failure in overall approach.

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Need to account for failure in overall approach.

Often can avoid failure altogether for explicit $\mathcal{D}$

Implementation Perspective

A weak learner takes a **distribution** $\mathcal{D}$
explicitly represented by examples $(x_i, y_i)_{i=1}^m$ and weights $\boldsymbol{w} \in \triangle_m$, and
outputs an $(\frac{1}{2} - \gamma)$-good hypothesis **deterministically**.

Boosting by Online Learning (BOL)

Fix

- A γ-weak learner $\mathcal{W}$ for $\mathcal{H}$.
- A sample $S = (x_i, y_i)_{i=1}^m$.
- A learner $\mathcal{A}$ for the dot loss game, e.g. Hedge.

Definition

For $t = 1, 2, \ldots, T$

- Get $\boldsymbol{w}_t$ from $\mathcal{A}$
- Get h_t from $\mathcal{W}$ applied to $\mathcal{D}^t(X = x, Y = y) = \sum_{i: x = x_i, y = y_i} w_t^i$
- Set $\ell_t^i = \mathbf{1}\{h_t(x_i) = y_i\}$.
- Send $\boldsymbol{\ell}_t$ to $\mathcal{A}$.

Output $h_S(x) = \text{sign}\left(\sum_{t=1}^T h_t(x)\right)$.

Duality: Experts $\Leftrightarrow$ data points   Rounds $\Leftrightarrow$ hypotheses.

BOL Analysis

Let R_T be a regret bound for $\mathcal{A}$.

Theorem (Zero training loss)

Consider BOL run for T rounds such that $\frac{R_T}{T} \leq \frac{\gamma}{2}$, with the weak learner error probability set to $\delta' = \frac{\delta}{T}$. Then

$$L_S(h_S) \ = \ 0$$

with probability $1 - \delta$ (over the possibly randomised weak learner)

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For the typical case $R_T = \sqrt{T \ln m}$ we find zero training loss after $T \geq \frac{4 \ln m}{\gamma^2}$ rounds.

BOL Analysis I

Suppose h_S misclassifies sample (x_i, y_i). Then

$$h_S(x_i) = \text{sign}\left(\sum_{t=1}^{T} h_t(x_i)\right) \neq y_i \quad \text{so that} \quad \sum_{t=1}^{T} \mathbf{1}\{h_t(x_i) = y_i\} \leq \frac{T}{2}$$

This means that

$$\min_j \sum_{t=1}^{T} \ell_t^j \;\leq\; \sum_{t=1}^{T} \mathbf{1}\{h_t(x_i) = y_i\} \;\leq\; \frac{T}{2}$$

and hence by the regret bound for $\mathcal{A}$,

$$\sum_{t=1}^{T} \boldsymbol{w}_t^{\intercal} \boldsymbol{\ell}_t \;\leq\; \frac{T}{2} + R_T \;\leq\; T\left(\frac{1}{2} + \frac{\gamma}{2}\right)$$

BOL Analysis II

Moreover

$$\sum_{t=1}^{T} \boldsymbol{w}_t^\intercal \boldsymbol{\ell}_t \;=\; \sum_{t=1}^{T}\sum_{j=1}^{m} w_t^j \mathbf{1}\left\{h_t(x_j) = y_j\right\}$$

In each round, we have

$$\boldsymbol{w}_t^\intercal \boldsymbol{\ell}_t \;=\; \sum_{j=1}^{m} w_t^j \mathbf{1}\left\{h_t(x_j) = y_j\right\} \;=\; 1 - L_{S,\boldsymbol{w}_t}(h_t)$$

The weak learner, with probability $\frac{\delta}{T}$ guarantees in each round

$$L_{S,\boldsymbol{w}_t}(h_t) \;\leq\; \frac{1}{2} - \gamma$$

Overall, with probability $\geq 1 - \delta$, we have

$$\sum_{t=1}^{T} \boldsymbol{w}_t^\intercal \boldsymbol{\ell}_t \;\geq\; T(1 - (\tfrac{1}{2} - \gamma)) \;=\; T(\tfrac{1}{2} + \gamma)$$

BOL Analysis III

But then we obtain the contradiction

$$T\left(\frac{1}{2}+\gamma\right) \;\leq\; T\left(\frac{1}{2}+\frac{\gamma}{2}\right)$$

So after all, h_S must be **perfect** on S.

AdaBoost

AdaBoost

In particular, do not want to assume knowledge of γ up front.

AdaBoost instead **computes** the empirical error:

$$\epsilon_t = \sum_{i=1}^{m} w_t^i \mathbf{1}\{h_t(x_i) \neq y_i\}$$

Fancy online learning method $\Rightarrow$ fancy boosting.

AdaBoost

Fix

- Aggregating Algorithm
- A γ-weak learner $\mathcal{W}$ for $\mathcal{H}$.
- A sample $S = (x_i, y_i)_{i=1}^m$.

Definition

For $t = 1, 2, \ldots, T$

- Get $\boldsymbol{w}_t$ from AA.
- Get h_t from $\mathcal{W}$ applied to $\mathcal{D}^t\left(X = x, Y = y\right) = \sum_{i:x=x_i,y=y_i} w_t^i$
- Compute error $\epsilon_t \ = \ \sum_{i=1}^m w_t^i \mathbf{1}\left\{h_t(x_i) \neq y_i\right\}$
- Sets the round-coefficient to $\alpha_t = \frac{1}{2} \ln\left(\frac{1}{\epsilon_t} - 1\right)$
- Set $\ell_t^i = \alpha_t y_i h_t(x_i)$.
- Send $\boldsymbol{\ell}_t$ to AA.

Output $h_S(x) = \text{sign}\left(\sum_{t=1}^T \alpha_t h_t(x)\right)$.

AdaBoost Result

Theorem

Suppose $\mathcal{W}$ γ-weak learns $\mathcal{H}$, i.e. $\epsilon_t \leq \frac{1}{2} - \gamma$. Then the training error after T rounds of AdaBoost is at most

$$L_S(h_s) \;\leq\; e^{-2\gamma^2 T}.$$

AdaBoost I

Get $\boldsymbol{w}_t$ by running AA on losses $\ell_t^i = \alpha_t y_i h_t(x_i)$. The mix loss in round t is

$$
\begin{aligned}
-\ln \sum_i w_t^i e^{-\ell_t^i} &= -\ln \left(\sum_i w_t^i e^{-\alpha_t y_i h_t(x_i)} \right) \\
&= -\ln \left(e^{-\alpha_t} \sum_{i: h_t(x_i) = y_i} w_t^i + e^{\alpha_t} \sum_{i: h_t(x_i) \neq y_i} w_t^i \right) \\
&= -\ln \left(e^{-\alpha_t} (1 - \epsilon_t) + e^{\alpha_t} \epsilon_t \right) \\
&\overset{\max_{\alpha_t}}{=} -\frac{1}{2} \ln \left(4 \epsilon_t (1 - \epsilon_t) \right) \\
&\overset{\text{assn.}}{\geq} -\frac{1}{2} \ln \left(1 - 4\gamma^2 \right) \\
&\geq 2\gamma^2
\end{aligned}
$$

AdaBoost II

Moreover, observe that

$$e^{-yf(x)} \;\geq\; \mathbf{1}\{yf(x) \leq 0\} \;=\; \mathbf{1}\{\text{sign}(f(x)) \neq y\}$$

Then by the AA telescope

$$\begin{aligned}
2\gamma^2 T \;&\leq\; -\ln\left(\sum_i \frac{1}{m} e^{-y_i \sum_{t=1}^{T} \alpha_t h_t(x_i)}\right) \\
&\leq\; -\ln\left(\sum_i \frac{1}{m}\mathbf{1}\left\{\text{sign}\left(\sum_{t=1}^{T} \alpha_t h_t(x_i)\right) \neq y_i\right\}\right) \\
&=\; -\ln\left(\sum_i \frac{1}{m}\mathbf{1}\{h_S(x_i) \neq y_i\}\right) \\
&=\; -\ln\left(L_S(h_S)\right)
\end{aligned}$$

AdaBoost Conclusion

Training error $< \frac{1}{m}$ means training error $= 0$.

We have $e^{-2\gamma^2 T} < \frac{1}{m}$ for

$$T > \frac{\ln m}{2\gamma^2}.$$

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Is 0 training error useful?

Risk

Is zero training loss good?

Should we worry about over-fitting?

The VC story

AdaBoost outputs

$$h_S(x) \;=\; \text{sign}\left(\sum_{t=1}^{T} \alpha_t h_t(x_i)\right)$$

A **half-space** classifier applied to **features** $(h_t(x))_{t=1}^{T}$.

Definition

Consider the class of all size T half-spaces over $\mathcal{B}$

$$L(\mathcal{B}, T) \;=\; \left\{ x \mapsto \text{sign}\left(\sum_{t=1}^{T} w_t h_t(x)\right) \middle| \boldsymbol{w} \in \mathbb{R}^T \text{ and } h_t \in \mathcal{B} \right\}$$

Capacity control

Boosting is safe.

Theorem

Let $d = \mathrm{VCdim}(\mathcal{B})$. *Then*

$$\mathrm{VCdim}\left(L(\mathcal{B}, T)\right) \;\leq\; 2(d+1)T\log_2\left(2(d+1)T\right)$$

Capacity control, Analysis

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Taking the log and solving (using the tangent bound) implies

$$m \;\leq\; 2(d+1)T \log_2 (2(d+1)T)$$

Conclusion

Conclusion

- Can boost weak learner to strong learner **efficiently**.
- Can hence compute ERM on big class from ERM on small class.
- Useful technique in theory/practice.
- Relation to margin theory (Chapter 15).