6.891: Lecture 17 (November 5th, 2003)

Theories of Generalization

Generalization

- So far in the couse, we've seen many ways to estimate parameters:
  - Maximum-likelihood estimation in language modeling, probabilistic context-free grammars, etc.
  - Smoothing of maximum-likelihood estimates:

$$P(dog \mid the, green) = \lambda_1 P_{ML} P(dog \mid the, green) + \lambda_2 P_{ML} P(dog \mid the) + \lambda_3 P_{ML} P(dog)$$

  - Perceptron, boosting, log-linear models for global linear models (feature selection, penalties for large parameter values)

- Today's lecture: theory and intuition behind various estimates

Overview

- A statistical framework
- Properties of maximum-likelihood estimates
- A first result, through Chernoff/Hoeffding bounds
- Generalization bounds for finite hypothesis spaces
- Structural Risk Minimization
- Generalization bounds for boosting
- Generalization bounds based on margins

The Basic Framework

- We have an input domain $\mathcal{X}$ and output domain $\mathcal{Y}$.
  e.g., $\mathcal{X}$ is a set of possible sentences, $\mathcal{Y}$ is set of possible parse trees.

- The task is to learn a function $F : \mathcal{X} \rightarrow \mathcal{Y}$

- We have a training set (x_i, y_i) where for $i = 1 \ldots m$ with $x_i \in \mathcal{X}$, $y_i \in \mathcal{Y}$

Loss functions

- Say we have a new test example x, whose true label is y
- The function $F(x)$ has the output $\hat{y}$
- A **loss function** is a function $L : \mathcal{Y} \times \mathcal{Y} \to \mathbb{R}$
- $L(\hat{y}, y)$ is cost of proposing $\hat{y}$ for an example x when y is the true label
- One example loss function: "0-1 loss"

$$L(\hat{y}, y) = \begin{cases} 0 & \text{If } y = \hat{y} \\ 1 & \text{otherwise} \end{cases}$$

- Another example: percentage of correct dependency relations in a parse

From now on, we'll assume $L(\hat{y}, y)$ is 0-1 loss

Empirical Loss

- We can now define the *empirical loss* of the function F, as

$$\hat{Er}(F) = \frac{1}{m}\sum_i L(F(x_i), y_i)$$

- $\hat{Er}(F)$ is the average loss on the training samples
- If L is the 0-1 loss, then $\hat{Er}(F)$ is the percentage of errors on the training sample

A Statistical Assumption

- We assume that both training and test samples are generated from some distribution $D(x, y)$
- $D(x, y)$ is fixed, but also unknown
- Crucial point: both training and test samples are drawn from the same distribution $D(x, y)$. This allows us to learn properties/functions from the training data which generalize to new, test examples

Expected Loss

- We now define the *expected loss* for a function F as

$$Er(F) = \sum_{x,y} D(x,y) L(F(x), y)$$

- If L is 0-1 loss, then $Er(F)$ is the *probability of an error* on a newly drawn test example

- $Er(F)$ is the measure of how "good" a function is: **our aim is to find an F such that $Er(F)$ is a low as possible**

Summary

- We have input/output domains $\mathcal{X}$ and $\mathcal{Y}$
- We assume there is some distribution $D(x, y)$ generating examples
- $(x_1, y_1) \ldots (x_m, y_m)$ is a training sample drawn from D
  this is the only evidence we have about D
- For any function $F : \mathcal{X} \rightarrow \mathcal{Y}$, we define

$$
\begin{aligned}
Er(F) &= \sum_{x,y} D(x, y) L(F(x), y) \\
\hat{E}r(F) &= \frac{1}{n} \sum_{i} L(F(x_i), y_i)
\end{aligned}
$$

- Our aim is to find a function F with a low value for $Er(F)$

The Bayes Optimal Hypothesis

- The *bayes optimal* function is

$$F_B(x) = \text{argmax}_y D(x, y)$$

- Intuition: for an input x, simply return the most likely label

- It can be shown that F_B has the lowest possible value for $Er(F)$

- We can never construct this function: it is a function of D, which is unknown. But it is a useful theoretical construct.

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Maximum-Likelihood Estimates

- In these approaches, we attempt to model the underlying distribution $D(x, y)$ or $D(y \mid x)$.

- We have *parameters* Θ, and a *model* $P(x, y \mid \Theta)$ or $P(y \mid x, \Theta)$. e.g.,

  – In probabilistic context-free grammars, the parameters are rule probabilities, and $P(x, y \mid \Theta)$ is a product of rule probabilities

  – In global log-linear models, we take

$$P(y \mid x, \Theta) = \frac{e^{\mathbf{\Phi}(x,y)\cdot\Theta}}{\sum_{y' \in \mathbf{GEN}(x)} e^{\mathbf{\Phi}(x,y')\cdot\Theta}}$$

- Given training samples (x_i, y_i), we maximize the log-likelihood

$$L(\Theta) = \sum_i \log P(x_i, y_i \mid \Theta) \quad \text{or} \quad L(\Theta) = \sum_i \log P(y_i \mid x_i, \Theta)$$

Justification for Maximum-Likelihood Estimates

- **Assumption:** There is some parameter setting Θ^* such that $D(x, y) = P(x, y \mid \Theta^*)$ or $D(y \mid x) = P(y \mid x, \Theta^*)$

- Define the maximum-likelihood estimates:

$$\Theta_{ML} = \text{argmax}_\Theta L(\Theta)$$

- A usual property of maximum-likelihood estimates: as the training sample size goes to ∞, then $P(x, y \mid \Theta_{ML})$ converges to $D(x, y)$ (or, $P(y \mid x, \Theta_{ML})$ converges to $D(y \mid x)$)

Justification for Maximum-Likelihood Estimates

It follows that:

- Given that
  - **Assumption 1:** There is some parameter setting Θ^* such that $D(x, y) = P(x, y \mid \Theta^*)$ or $D(y \mid x) = P(y \mid x, \Theta^*)$
  - **Assumption 2:** we have enough training data for the maximum likelihood estimates to converge

- Then $P(x, y \mid \Theta_{ML})$ converges to $D(x, y)$, and

$$\text{argmax}_y P(x, y \mid \Theta_{ML})$$

converges to the Bayes-optimal function

$$F_B = \text{argmax}_y D(x, y)$$

(and similar properties follow for conditional models $P(y \mid x, \Theta)$)

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Estimating the Expected Loss

- We'd like to know what

$$Er(F) = \sum_{x,y} D(x,y) L(F(x), y)$$

  is for some function F

- A natural estimate of $Er(F)$ is

$$\hat{E}r(F) = \frac{1}{n} \sum_{i} L(F(x_i), y_i)$$

Question: how good an estimate is $\hat{E}r(F)$?

Chernoff/Hoeffding Bounds

- Say we have a coin with (unknown) probability of heads $= p$
- We derive an estimate of p by the following procedure:
  - Toss the coin m times
  - If we see heads h times, our estimate is

$$\hat{p} = \frac{h}{m}$$

- How good is this estimate? **Answer: for all** ϵ, p, m

$$P[|p - \hat{p}| > \epsilon] \leq 2e^{-2m\epsilon^2}$$

  where the probability P is taken over the generation of the training sample of m coin tosses

- Additional bounds:

$$P[p - \hat{p} > \epsilon] \leq e^{-2m\epsilon^2}$$

$$P[\hat{p} - p > \epsilon] \leq e^{-2m\epsilon^2}$$

- An example: say we take $m = 1000$, and $\epsilon = 0.05$. Then

$$e^{-2m\epsilon^2} = e^{-5} \approx \frac{1}{148}$$

- Then if we repeatedly take samples of size 1000, for (roughly) 147/148 samples we will have $(p - \hat{p}) \leq 0.05$, for 147/148 samples we will have $(\hat{p} - p) \leq 0.05$, for 146/148 samples we will have $|\hat{p} - p| \leq 0.05$

- Put another way: our estimation procedure has probability $2e^{-5} \approx 2/148$ of returning a value of $\hat{p}$ that is not within 0.05 of p.

- We derive an estimate of p by the following procedure:
  - Toss the coin m times
  - If we see heads h times, our estimate is

$$\hat{p} = \frac{h}{n}$$

Estimating the Expected Loss

- We'd like to know value of $Er(F) = \sum_{x,y} D(x,y)L(F(x),y)$ for some function F
- A natural estimate of $Er(F)$ is $\hat{E}r(F) = \frac{1}{m}\sum_i L(F(x_i),y_i)$
- From Chernoff/Hoeffding bounds:

$$P[\hat{E}r(F) - Er(F) > \epsilon] \leq e^{-2m\epsilon^2}$$

Converting this Result to a Confidence Interval

- Introduce a variable $0 < \delta < 1$, which is

$$\delta = e^{-2m\epsilon^2}$$

next, solve for ϵ, giving

$$\epsilon = \sqrt{\frac{\log \frac{1}{\delta}}{2m}}$$

Theorem: For a single hypothesis F, for any distribution $D(x, y)$, for any $\delta > 0$, with probability at least $1 - \delta$ over the choice of the training sample,

$$Er(F) \leq \hat{E}r(F) + \sqrt{\frac{\log \frac{1}{\delta}}{2m}}$$

An Example

- Say we measure $\hat{E}r(F) = 0.25$ from a sample of size 1000. We take $\delta = 0.01$. Then with probability at least $1 - \delta = 99\%$,

$$Er(F) \leq 0.25 + \sqrt{\frac{\log \frac{1}{\delta}}{2m}} = 0.25 + 0.048 = 0.298$$

We have to be careful!

- It's tempting to choose (train) a function F using the training sample, then use the previous bound to estimate its error

- **But** in this case the function F depends on the training sample, and the bound isn't valid

- The bound is only valid if $Er(F)$ and $\hat{E}r(F)$ are calculated from a sample that is independent of F

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Hypothesis Spaces

- A **hypothesis space** $\mathcal{H}$ is a set of functions mapping $\mathcal{X}$ to $\mathcal{Y}$
- Learning from a training set $\equiv$ choosing a member of $\mathcal{H}$ based on the training set
- We'll first consider finite hypothesis spaces

- Example of an infinite hypothesis space:
  given **GEN**, $\mathbf{\Phi}$, **W**, define

$$F_{\mathbf{W}}(x) = \mathrm{argmax}_{y \in \mathbf{GEN}(x)} \mathbf{\Phi}(x, y) \cdot \mathbf{W}$$

- For every member of $\mathbf{W} \in \mathbb{R}^d$, we have a different function

- An infinite hypothesis space is

$$\mathcal{H} = \{F_{\mathbf{W}} \; : \; \mathbf{W} \in \mathbb{R}^d\}$$

- Note that if we store each element of $\mathbf{W}$ to b bits of precision, then this becomes a finite hypothesis class of size $|\mathcal{H}| = 2^{db}$

Choosing Between the Members of $\mathcal{H}$

- An obvious choice: choose

$$F_{ERM} = \arg\min_{F \in \mathcal{H}} \hat{E}r(F)$$

  i.e., choose the member of $\mathcal{H}$ which has lowest training error

- This method is called "Empirical Risk Minimization" ([Vapnik, 1995])

- Next question: how good is $\hat{E}r(F_{ERM})$ as an estimate of $Er(F_{ERM})$?

Choosing Between the Members of $\mathcal{H}$

- Chernoff/Hoeffding bounds for a single hypothesis:

$$P[\hat{E}r(F) - Er(F) > \epsilon] \leq e^{-2m\epsilon^2}$$

- A new bound for finite hypothesis spaces:

$$P[\max_{F \in \mathcal{H}} \left(\hat{E}r(F) - Er(F)\right) > \epsilon] \leq |\mathcal{H}| e^{-2m\epsilon^2}$$

Intuition: if we have $|\mathcal{H}|$ functions, there is $|\mathcal{H}|$ times the probability that at least one of them will have a value for $\hat{E}r(F)$ that deviates by at least ϵ from $Er(F)$

A Proof

- The **union bound** says that for any events $A_1, A_2, \ldots A_n$,

$$P(A_1 \text{ or } A_2 \text{ or } \cdots \text{ or } A_n) \leq \sum_{i=1}^{n} P(A_i)$$

- Say we have n functions in $\mathcal{H}$, numbered $F_1, F_2, \ldots F_n$
- Note that $\left[\max_{F \in \mathcal{H}} \left(\hat{Er}(F) - Er(F)\right)\right] > \epsilon$ if and only if

$$\begin{aligned}
\hat{Er}(F_1) - Er(F_1) &> \epsilon \quad \text{or} \\
\hat{Er}(F_2) - Er(F_2) &> \epsilon \quad \text{or} \\
&\ldots \\
\hat{Er}(F_n) - Er(F_n) &> \epsilon
\end{aligned}$$

- By the union bound, the probability of at least one of these events happening is at most

$$\sum_i P(\hat{Er}(F_i) - Er(F_i) > \epsilon) = |\mathcal{H}| e^{-2m\epsilon^2}$$

Theorem: For any finite hypothesis class $\mathcal{H}$, distribution $D(x, y)$, and $\delta > 0$, with probability at least $1 - \delta$ over the choice of training sample, for all $F \in \mathcal{H}$,

$$Er(F) \leq \hat{E}r(F) + \sqrt{\frac{\log|\mathcal{H}| + \log\frac{1}{\delta}}{2m}}$$

Theorem: For any finite hypothesis class $\mathcal{H}$, distribution $D(x, y)$, and $\delta > 0$, with probability at least $1 - \delta$ over the choice of training sample, for all $F \in \mathcal{H}$,

$$Er(F) \leq \hat{E}r(F) + \sqrt{\frac{\log|\mathcal{H}| + \log\frac{1}{\delta}}{2m}}$$

An example: say we have a hypothesis class $\mathcal{H}$ of size 1000. We have 10,000 training examples. For each function in $\mathcal{H}$, we measure the error on the training examples, $\hat{E}r(F)$. Say we choose $\delta = 0.01$. In this scenario we have

$$\sqrt{\frac{\log|\mathcal{H}| + \log\frac{1}{\delta}}{2m}} = 0.00239$$

and for $1 - \delta = 99\%$ of all experiments with a sample of size $10,000$, we will have

$$Er(F) \leq \hat{E}r(F) + 0.00239$$

for all members of $\mathcal{H}$

Corollary: For any finite hypothesis class $\mathcal{H}$, distribution $D(x, y)$, and $\delta > 0$, with probability at least $1 - \delta$ over the choice of training sample,

$$Er(F_{ERM}) \leq \hat{E}r(F_{ERM}) + \sqrt{\frac{\log|\mathcal{H}| + \log\frac{1}{\delta}}{2m}}$$

where

$$F_{ERM} = \arg\min_{F \in \mathcal{H}} \hat{E}r(F)$$

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Another Look at the Bound

Corollary: For any finite hypothesis class $\mathcal{H}$, distribution $D(x, y)$, and $\delta > 0$, with probability at least $1 - \delta$ over the choice of training sample,

$$Er(F_{ERM}) \leq \hat{E}r(F_{ERM}) + \sqrt{\frac{\log|\mathcal{H}| + \log\frac{1}{\delta}}{2m}}$$

where $F_{ERM} = \arg\min_{F \in \mathcal{H}} \hat{E}r(F)$

- Crucial point: as $|\mathcal{H}|$ becomes larger, the number of training examples required for F_{ERM} to be reliable increases.

Comparison to the Bayes Optimal Hypothesis

- Say F^* is the best function in the hypothesis space

$$F^* = \arg\min_{F \in \mathcal{H}} Er(F)$$

- How close are we to the Bayes optimal hypothesis?

$$Er(F_{ERM}) - Er(F_B)$$

$$= \underbrace{(Er(F_{ERM}) - Er(F^*))}_{\text{Variance term}} + \underbrace{(Er(F^*) - Er(F_B))}_{\text{Bias term}}$$

- Tension:
  - If $\mathcal{H}$ is too large, variance term is likely to be large
  - If $\mathcal{H}$ is too small, bias term is likely to be large
    (less chance of a "good" function being in our hypothesis space)

A Compromise: Structural Risk Minimization

- First step: pick a *series* of hypothesis classes of increasing size, $\mathcal{H}_1, \mathcal{H}_2, \mathcal{H}_3 \ldots \mathcal{H}_s$, where $|\mathcal{H}_1| < |\mathcal{H}_2| < \cdots < |\mathcal{H}_s|$.
  (This step must be done independently from the training sample)

Theorem: Assume a set of finite hypothesis classes $\mathcal{H}_1, \mathcal{H}_2 \ldots \mathcal{H}_s$, and some distribution $D(x, y)$. For all $i = 1 \ldots s$, for all hypotheses $F \in \mathcal{H}_i$, with probability at least $1 - \delta$ over the choice of training set of size m drawn from D,

$$Er(F) \leq \hat{Er}(F) + \sqrt{\frac{\log |\mathcal{H}_i| + \log \frac{1}{\delta} + \log s}{2m}}$$

A Compromise: Structural Risk Minimization

- Pick the hypothesis that minimizes the bound, i.e.,

$$F_{SRM} = \arg\min_{F} \left(\hat{E}r(F) + \sqrt{\frac{\log |\mathcal{H}_i| + \log \frac{1}{\delta} + \log s}{2m}} \right)$$

- The bound has two components

$$\underbrace{\hat{E}r(F)}_{\text{Fit to training data}} \quad + \quad \underbrace{\sqrt{\frac{\log |\mathcal{H}_i| + \log \frac{1}{\delta} + \log s}{2m}}}_{\text{Penalty for complexity}}$$

- Some points:
  - The "complexity" of a function is related to the size of the hypothesis space of which it is a member
  - The complexity of F is also related to the reliability of $\hat{E}r(F)$ as an estimate of $Er(F)$

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Back to Global Linear Models

- Example of an infinite hypothesis space:
  given $\mathbf{GEN}$, $\mathbf{\Phi}$, $\mathbf{W}$, define

$$F_{\mathbf{W}}(x) = \text{argmax}_{y \in \mathbf{GEN}(x)} \mathbf{\Phi}(x, y) \cdot \mathbf{W}$$

- For every member of $\mathbf{W} \in \mathbb{R}^d$, we have a different function

- An infinite hypothesis space is

$$\mathcal{H} = \{F_{\mathbf{W}} \ : \ \mathbf{W} \in \mathbb{R}^d\}$$

Back to Global Linear Models

- For now, we'll "cheat" by considering $\mathcal{H}$ to be finite
- We do this by assuming that we store each element of $\mathbf{W}$ to b bits of precision, then this becomes a finite hypothesis class of size $|\mathcal{H}| = 2^{db}$
- We can then apply our previous theorem:

Theorem: For a global linear model with finite hypothesis class $\mathcal{H}$ (d parameters at b bits of precision), distribution $D(x, y)$, and $\delta > 0$, with probability at least $1 - \delta$ over the choice of training sample, for all $F \in \mathcal{H}$,

$$Er(F) \leq \hat{E}r(F) + \sqrt{\frac{\log|\mathcal{H}| + \log\frac{1}{\delta}}{2m}} = \hat{E}r(F) + \sqrt{\frac{db\log 2 + \log\frac{1}{\delta}}{2m}}$$

- The theorem implies that $d \times b \times \log 2$ must be small compared to $2m$ where m is the sample size.

- In many of our experiments (e.g., parse reranking) we have many features, so d is huge $\Rightarrow$ the bound implies that choosing F_{ERM} is *bad*

- Instead, we balanced fit to the training data against some penalty for "complexity":
  - In boosting, minimize an upper bound on the training error while using a small number of features
  - In log-linear models, maximize likelihood while keeping parameter values small

A Bound for Feature-Selection Methods

- Before, our hypothesis class was

$$\mathcal{H} = \{F_{\mathbf{W}} \; : \; \mathbf{W} \in \mathbb{R}^d\}$$

which has 2^{bd} members if we store parameters to b bits of precision

- Now, consider a restricted hypothesis space:

$$\mathcal{H}_k = \{F_{\mathbf{W}} \; : \; \mathbf{W} \in \mathbb{R}^d, \text{only } k \text{ parameters have non-zero values}\}$$

- What is the size of $\mathcal{H}_k$ under precision b for the parameters?

A Bound for Feature-Selection Methods

- There are
$$C_k^d = \begin{pmatrix} d \\ k \end{pmatrix} = \frac{d!}{(d-k)!k!}$$
ways of choosing k features out of d features in total

- For each choice of k features, there are 2^{kb} ways of setting their parameters given b bits of precision

- It follows that
$$|\mathcal{H}_k| = C_k^d \times 2^{kb}$$
and
$$\log|\mathcal{H}_k| = \log C_k^d + kb \log 2$$

A Bound for Feature-Selection Methods

- Also, note that

$$C_k^d < d^k$$
$$\Rightarrow \log C_k^d < k \log d$$

- Giving:

$$\begin{aligned} \log |\mathcal{H}_k| &= \log C_k^d + kb \log 2 \\ &< k \log d + kb \log 2 \\ &= k(\log d + b \log 2) \end{aligned}$$

Theorem: For a global linear model with finite hypothesis class $\mathcal{H}_k$ (d parameters at b bits of precision, with k non-zero parameters), distribution $D(x, y)$, and $\delta > 0$, with probability at least $1 - \delta$ over the choice of training sample, for all $F \in \mathcal{H}$,

$$Er(F) \leq \hat{E}r(F) + \sqrt{\frac{\log |\mathcal{H}_k| + \log \frac{1}{\delta}}{2m}} = \hat{E}r(F) + \sqrt{\frac{k(\log d + b \log 2) + \log \frac{1}{\delta}}{2m}}$$

Theorem: For a global linear model with finite hypothesis class $\mathcal{H}_k$ (d parameters at b bits of precision, with k non-zero parameters), distribution $D(x, y)$, and $\delta > 0$, with probability at least $1 - \delta$ over the choice of training sample, for all $F \in \mathcal{H}_k$,

$$Er(F) \leq \underbrace{\hat{E}r(F)}_{\text{Fit to training data}} + \underbrace{\sqrt{\frac{k(\log d + b \log 2) + \log \frac{1}{\delta}}{2m}}}_{\text{Complexity penalty}}$$

- Complexity penalty is *linear* in k, but *logarithmic* in d: $\Rightarrow$ we can have a very large number of features (d can be large) as long as only a small number are selected (k is small)
- One justification for **Boosting** is that it minimizes this kind of bound

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Back to Margins

- We can think of the training data (x_i, y_i), and **GEN**, providing a set of good/bad parse pairs

$$(x_i, y_i, z_{i,j}) \quad \text{for } i = 1 \ldots n,\ j = 1 \ldots n_i$$

- The **Margin** on example $z_{i,j}$ under parameters $\mathbf{W}$ is

$$\mathbf{m_{i,j}}(\mathbf{W}) = \mathbf{\Phi}(x_i, y_i) \cdot \mathbf{W} - \mathbf{\Phi}(x_i, z_{i,j}) \cdot \mathbf{W}$$

- A couple more definitions:

$$\mathbf{m_i}(\mathbf{W}) = \min_j \mathbf{m_{i,j}}(\mathbf{W})$$

$$\hat{E}r(\mathbf{W}, \gamma) = \frac{1}{m} \sum_i [[\mathbf{m_i}(\mathbf{W}) < \gamma]]$$

- So, $\mathbf{m_i}(\mathbf{W})$ is the minimum margin on the i'th example
- $\hat{E}r(\mathbf{W}, \gamma)$ is the percentage of examples whose minimum margin is less than γ

Theorem: Assume the hypothesis class $\mathcal{H}$ is as defined above, and that there is some distribution $D(x, y)$ generating examples. For all $F_{\mathbf{W}} \in \mathcal{H}$, for all $\gamma > 0$, with probability at least $1 - \delta$ over the choice of training set of size m drawn from D,

$$Er(F_{\mathbf{W}}) \leq \hat{Er}(\mathbf{W}, \gamma) + O\left(\sqrt{\frac{1}{m}\left(\frac{R^2||\mathbf{W}||^2}{\gamma^2}(\log m + \log N) + \log\frac{1}{\delta}\right)}\right)$$

where R is a constant such that $\forall x \in \mathcal{X}, \forall y \in \mathbf{GEN}(x), \forall z \in \mathbf{GEN}(x)$, $||\mathbf{\Phi}(x, y) - \mathbf{\Phi}(x, z)|| \leq R$. The variable N is the smallest positive integer such that $\forall x \in \mathcal{X}, |\mathbf{GEN}(x)| - 1 \leq N$.

Notes on the bound

$$Er(F_{\mathbf{W}}) \leq \underbrace{\hat{E}r(\mathbf{W}, \gamma)}_{\text{Fit to the data}} + \underbrace{O\left(\sqrt{\frac{1}{m}\left(\frac{R^2||\mathbf{W}||^2}{\gamma^2}(\log m + \log N) + \log\frac{1}{\delta}\right)}\right)}_{\text{Complexity Penalty}}$$

- The complexity penalty does not (directly) depend on the number of parameters in the model

- The bound has two conflicting terms: keep the margin $\mathbf{m_i}(\mathbf{W})$ high on as many examples as possible, but keep $||\mathbf{W}||^2$ low.

- The dependence on $\log N$ is *bad*: perhaps the bound can be improved?

Notes on the bound

$$Er(F_{\mathbf{W}}) \leq \underbrace{\hat{E}r(\mathbf{W}, \gamma)}_{\text{Fit to the data}} + \underbrace{O\left(\sqrt{\frac{1}{m}\left(\frac{R^2||\mathbf{W}||^2}{\gamma^2}(\log m + \log N) + \log\frac{1}{\delta}\right)}\right)}_{\text{Complexity Penalty}}$$

- Note the relationship to global log-linear models with a gaussian prior:

$$\mathbf{W}_{MAP} = \operatorname{argmax}_{\mathbf{W}}\left(L(\mathbf{W}) - C||\mathbf{W}||^2\right)$$

where

$$\begin{aligned} L(\mathbf{W}) &= \sum_i \log P(y_i \mid x_i, \mathbf{W}) \\ &= -\sum_i \log\left(1 + \sum_j e^{-\mathbf{m_{i,j}}(\mathbf{W})}\right) \end{aligned}$$

Summary

- One assumption: the same distribution $D(x, y)$ is generating training and test examples

- $Er(F)$ is the error rate w.r.t. this distribution: we would like to find an F which minimizes this. $\hat{E}r(F)$ is the error rate on the training sample

- Started considering how good an estimate $\hat{E}r(F)$ is of $Er(F)$. This depends on the **complexity** of F.

- "Structural risk minimization" means we search for a function which has a low value for $\hat{E}r(F)$, but is also not too "complex"

- Several measures of complexity have been considered:

  - Size of hypothesis class the function comes from
  - Number of non-zero parameter values
  - Size of the margins on training examples vs. $||\mathbf{W}||^2$

Some Final Points

- Advantage of these bounds is that they make very few assumptions (for example, no assumptions about $D(x, y)$)
- Disadvantage is that they can be very pessimistic, or "loose"
- A great deal of current research on how to get "tighter" bounds
- The bounds were originally developed for *classification* problems: several important issues remain for NLP, e.g.,
  - Results for loss functions other than $0 - 1$ loss
  - Dependence on $\log |\mathbf{GEN}(x)|$ in margin bounds
  - How to optimize the bounds in practice