

# **SDS 384 11: Theoretical Statistics**

## **Lecture 16: Uniform Law of Large Numbers- Dudley's chaining Introduction**

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# Rademacher complexity of function classes

## Example

Suppose  $\mathcal{F}$  is a class parametric functions  $\mathcal{F} := \{f(\theta, \cdot) : \theta \in B_2\}$ , where  $B_2$  is the unit  $L_2$  ball in  $\mathbb{R}^d$ . Assume that  $\mathcal{F}$  is closed under negation.  $f$  is  $L$  Lipschitz w.r.t. the Euclidean distance on  $\Theta$ , i.e.

$$|f(\theta, \cdot) - f(\theta', \cdot)| \leq L\|\theta - \theta'\|_2.$$

$$\mathcal{R}_n(\mathcal{F}) = O\left(L\sqrt{\frac{d \log(Ln)}{n}}\right)$$

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- How do we do this?
- Using covering numbers. But we need to define a bunch of stuff first.

# A Stochastic Process

- Consider a set  $\mathcal{T} \subseteq \mathcal{R}^d$ .
- The family of random variables  $\{X_\theta : \theta \in \mathcal{T}\}$  define a Stochastic process indexed by  $\mathcal{T}$ .

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- The family of random variables  $\{X_\theta : \theta \in \mathcal{T}\}$  define a Stochastic process indexed by  $\mathcal{T}$ .
- We are often interested in the behavior of this process given its dependence on the structure of the set  $\mathcal{T}$ .
- In the other direction, we want to know the structure of  $\mathcal{T}$  given the behavior of this process.

## Definition

A canonical Gaussian process indexed by  $\mathcal{T}$  is defined as:

$$G_\theta := \langle z, \theta \rangle = \sum_k z_k \theta_k,$$

where  $z_k \stackrel{\text{iid}}{\sim} N(0, 1)$ . The supremum  $\mathcal{G}(\mathcal{T}) := E_z[\sup_{\theta \in \mathcal{T}} G_\theta]$  is the Gaussian complexity of  $\mathcal{T}$ .

# Rademacher complexity

- Replacing the iid standard normal variables by iid Rademacher random variables gives a Rademacher process  $\{R_\theta, \theta \in \mathcal{T}\}$ , where

$$R_\theta := \langle \epsilon, \theta \rangle = \sum_k \epsilon_k \theta_k, \quad \text{where } \epsilon_k \stackrel{\text{iid}}{\sim} \text{Uniform}\{-1, 1\}$$

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- $\mathcal{R}(\mathcal{T}) := E_\epsilon[\sup_{\theta \in \mathcal{T}} R_\theta]$  is called the Rademacher complexity of  $\mathcal{T}$ .



## How does this relate to the former notions of Rademacher complexity?

- Recall that

$$\mathcal{R}_{\mathcal{F}} := E[\sup_{f \in \mathcal{F}} |\sum_i \epsilon_i f(X_i)|] = E[E[\sup_{f \in \mathcal{F}} |\sum_i \epsilon_i f(X_i)| | X_1, \dots, X_n]]$$

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- Now the inner expectation can be upper bounded by

$$E_{\epsilon} \sup_{\theta \in \mathcal{T} \cup -\mathcal{T}} \sum_i \epsilon_i \theta_i, \text{ where } \mathcal{T} \subseteq \mathbb{R}^n \text{ can be written as}$$

$$\mathcal{T} = \{(f(X_1), \dots, f(X_n)) \mid f \in \mathcal{F}\}$$

## Theorem

For  $\mathcal{T} \in \mathbb{R}^d$ ,

$$\mathcal{R}(\mathcal{T}) \leq \sqrt{\frac{\pi}{2}} \mathcal{G}(\mathcal{T}) \leq c \sqrt{\log d} \mathcal{R}(\mathcal{T})$$

- This is showing that there can be there are some sets where the Gaussian complexity can be substantially larger than the Rademacher complexity.
- We will in fact give an example.

## Proof (of first inequality)

$$\begin{aligned}\mathcal{G}(\mathcal{T}) &= E \sup_{\theta \in \mathcal{T}} \sum_i z_i \theta_i \\ &= E_{\epsilon} E_Z \sup_{\theta \in \mathcal{T}} \sum_i \epsilon_i |z_i| \theta_i \\ &\geq E_{\epsilon} \sup_{\theta \in \mathcal{T}} \sum_i \epsilon_i E |z_i| \theta_i \\ &= \sqrt{\frac{2}{\pi}} \mathcal{R}(\mathcal{T})\end{aligned}$$

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Consider the  $L_1$  ball in  $\mathcal{R}^d$  denoted by  $B_1^d$ .

$$\mathcal{R}(B_1^d) = 1, \mathcal{G}(B_1^d) \leq \sqrt{2 \log d}$$

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$$\mathcal{R}(B_1^d) = 1, \mathcal{G}(B_1^d) \leq \sqrt{2 \log d}$$

- $\mathcal{R}(B_1^d) = E\left[\sup_{\|\theta\|_1 \leq 1} \sum_i \theta_i \epsilon_i\right] = E[\|\epsilon\|_\infty] = 1$
- Similarly,  $\mathcal{G}(B_1^d) = E[\|z\|_\infty]$

## Recall the finite class lemma?

### Theorem

*Consider  $z$  with independent standard normal components.*

$$E \max_{a \in A} \langle z, a \rangle \leq \max_{a \in A} \|a\| \sqrt{2 \log |A|}$$



## Recall the finite class lemma?

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$$E \max_{a \in A} \langle z, a \rangle \leq \max_{a \in A} \|a\| \sqrt{2 \log |A|}$$

- In our case,  $A = \{e_i, i \in [d]\}$ ,  $e_i(j) = \pm 1(j = i)$ ,  $|A| = 2d$  and  $\max_{a \in A} \|a\| = 1$ .
- This gives a weaker bound on the Gaussian complexity.

# A sub-gaussian process

## Definition

A stochastic process  $\theta \rightarrow X_\theta$  with indexing set  $T$  is sub-Gaussian w.r.t a metric  $d_X$  if  $\forall \theta, \theta' \in T$  and  $\lambda \in \mathbb{R}$ ,

$$E \exp(\lambda(X_\theta - X_{\theta'})) \leq \exp\left(\frac{\lambda^2 d_X(\theta, \theta')^2}{2}\right)$$

- This immediately implies the following tail bound.

$$P(|X_\theta - X_{\theta'}| \geq t) \leq 2 \exp\left(-\frac{t^2}{2d_X(\theta, \theta')^2}\right)$$

# Upper bound by 1 step discretization

## Theorem

(1-step discretization bound). Let  $\{X_\theta, \theta \in \mathcal{T}\}$  be a zero-mean sub-Gaussian process with respect to the metric  $d_X$ . Then for any  $\delta > 0$ , we have

$$E \left[ \sup_{\theta, \theta' \in \mathcal{T}} (X_\theta - X_{\theta'}) \right] \leq 2E \left[ \sup_{\substack{\theta, \theta' \in \mathcal{T} \\ d_X(\theta, \theta') \leq \delta}} (X_\theta - X_{\theta'}) \right] + 2D \sqrt{\log N(\delta; \mathcal{T}, d_X)},$$

where  $D := \max_{\theta, \theta' \in \Theta} d_X(\theta, \theta')$ .

- The mean zero condition gives us:

$$E[\sup_{\theta \in \mathcal{T}} X_\theta] = E[\sup_{\theta \in \mathcal{T}} (X_\theta - X_{\theta_0})] \leq E[\sup_{\theta, \theta' \in \mathcal{T}} (X_\theta - X_{\theta'})]$$

$$E \left[ \sup_{\theta, \theta' \in \mathcal{T}} (X_\theta - X_{\theta'}) \right] \leq \underbrace{2 E \left[ \sup_{\substack{\theta, \theta' \in \mathcal{T} \\ d_X(\theta, \theta') \leq \delta}} (X_\theta - X_{\theta'}) \right]}_{\text{Approximation error}} + \underbrace{4 \sqrt{D^2 \log N(\delta; \mathcal{T}, d_X)}}_{\text{Estimation error}}$$

- As  $\delta \rightarrow 0$ , the cover becomes more refined, and so the approximation error decays to zero.
- But the estimation error grows.
- In practice the  $\delta$  can be chosen to achieve the optimal trade-off between two terms.

- Choose a  $\delta$  cover  $T$ .
- For  $\theta, \theta' \in \mathcal{T}$ , let  $\theta^1, \theta^2 \in T$  such that  $d_X(\theta, \theta^1) \leq \delta$  and  $d_X(\theta', \theta^2) \leq \delta$ .

$$\begin{aligned} X_\theta - X_{\theta'} &= (X_\theta - X_{\theta^1}) + (X_{\theta^1} - X_{\theta^2}) + (X_{\theta^2} - X_{\theta'}) \\ &\leq 2 \sup_{\substack{\theta, \theta' \in \mathcal{T} \\ d_X(\theta, \theta') \leq \delta}} (X_\theta - X_{\theta'}) + \sup_{\theta^1, \theta^2 \in T} (X_{\theta^1} - X_{\theta^2}) \end{aligned}$$

- But note that  $X_{\theta^1} - X_{\theta^2} \sim \text{Subgaussian with variance proxy } (d_X(\theta^1, \theta^2))..$

# Finite class lemma for subgaussian processes

## Theorem

Consider  $X_\theta$  sub-gaussian w.r.t  $d$  on  $\mathcal{T}$  and  $A$  is a set of pairs from  $\mathcal{T}$ .

$$E \max_{(\theta, \theta') \in A} (X_\theta - X_{\theta'}) \leq D \sqrt{2 \log |A|},$$

where  $D := \max_{(\theta, \theta') \in A} d_X(\theta, \theta')$ .

## Finite class lemma

$$\begin{aligned}\exp\left(\lambda E \max_{(\theta, \theta') \in A} (X_\theta - X_{\theta'})\right) &\leq E \exp\left(\lambda \max_{(\theta, \theta') \in A} (X_\theta - X_{\theta'})\right) \\ &= \max_{(\theta, \theta') \in A} E \exp(\lambda(X_\theta - X_{\theta'})) \\ &\leq \sum_{(\theta, \theta') \in A} \exp\left(\frac{\lambda^2 d_X(\theta, \theta')^2}{2}\right) \\ &\leq |A| \exp\left(\frac{\lambda^2 D^2}{2}\right)\end{aligned}$$

- Now optimize over  $\lambda$ .

## Finishing the proof

$$X_\theta - X_{\theta'} \leq 2 \sup_{\substack{\theta, \theta' \in \mathcal{T} \\ d_X(\theta, \theta') \leq \delta}} (X_\theta - X_{\theta'}) + \sup_{\theta^i, \theta^j \in \mathcal{T}} (X_{\theta^1} - X_{\theta^2})$$

$$\begin{aligned} E \left[ \sup_{\theta, \theta' \in \mathcal{T}} (X_\theta - X_{\theta'}) \right] &\leq 2E \left[ \sup_{\substack{\theta, \theta' \in \mathcal{T} \\ d_X(\theta, \theta') \leq \delta}} (X_\theta - X_{\theta'}) \right] + E \left[ \sup_{\theta^i, \theta^j \in \mathcal{T}} (X_{\theta^1} - X_{\theta^2}) \right] \\ &\leq 2E \left[ \sup_{\substack{\theta, \theta' \in \mathcal{T} \\ d_X(\theta, \theta') \leq \delta}} (X_\theta - X_{\theta'}) \right] + D \sqrt{2 \log N(\delta; \mathcal{T}, d_X)^2} \end{aligned}$$



## Revisiting: smoothly parametrized class

### Example

Suppose  $\mathcal{F}$  is a class parametric functions  $\mathcal{F} := \{f(\theta, \cdot) : \theta \in B_2\}$ , where  $B_2$  is the unit  $L_2$  ball in  $\mathbb{R}^d$ . Assume that  $\mathcal{F}$  is closed under negation.  $f$  is  $L$  Lipschitz w.r.t. the Euclidean distance on  $\Theta$ , i.e.

$$|f(\theta, \cdot) - f(\theta', \cdot)| \leq L\|\theta - \theta'\|_2.$$

$$\mathcal{R}_n(\mathcal{F}) = O\left(L\sqrt{\frac{d \log(Ln)}{n}}\right)$$

- Denote  $f(\theta, X_1^n)$  as the vector  $(f(\theta, X_1), \dots, f(\theta, X_n))$ .
- Recall that  $n\mathcal{R}_n(\mathcal{F}) = E \left[ \sup_{f \in \mathcal{F}} \langle \epsilon, f(\theta, X_1^n) \rangle \right] = E \left[ \sup_{\theta \in \Theta} \langle \epsilon, f(\theta, X_1^n) \rangle \right]$
- The process  $f(\theta, X_1^n) \rightarrow \langle \epsilon, f(\theta, X_1^n) \rangle =: Y_\theta$  is mean zero subgaussian.
- Note that  $Y_\theta - Y_{\theta'} \sim \text{Subgaussian with var proxy } d_X(\theta, \theta')^2$
- We have:

$$d_X(\theta, \theta') = \|f(\theta, X_1^n) - f(\theta', X_1^n)\|^2 \leq nL^2 \|\theta - \theta'\|_2^2$$

- So it is  $L\sqrt{n}$  Lipschitz.

- Also,

$$n\mathcal{R}_n(\mathcal{F}) = E[\sup_{\theta \in \Theta} (Y_\theta - Y_{\theta'})] \leq E[\sup_{\theta, \theta' \in \Theta} (Y_\theta - Y_{\theta'})]$$

•

$$n\mathcal{R}_n(\mathcal{F}) \leq \underbrace{2E \sup_{\substack{d_X(\theta, \theta') \leq \delta \\ \theta, \theta' \in \Theta}} (Y_\theta - Y_{\theta'})}_A + 2D\sqrt{\log N(\delta; \mathcal{F}(\Theta, X_1^n), d_X)}$$

- $A \leq \delta E \left[ \sup_{\|v\|_2=1} \langle \epsilon, v \rangle \right] \leq \delta \sqrt{n}$

- $D = \sup_{\theta, \theta'} d_X(\theta, \theta') = 2L\sqrt{n}$

- $N(\delta; \mathcal{F}, d_X) \leq N(\delta/L\sqrt{n}, \Theta, \|\cdot\|_2) \leq \left(1 + \frac{L\sqrt{n}}{\delta}\right)^d$
- Finally,

$$\mathcal{R}_n(\mathcal{F}) \leq \frac{4\delta}{\sqrt{n}} + 4L\sqrt{\frac{d \log(1 + L\sqrt{n}/\delta)}{n}}$$

- Setting  $\delta = 1$  gives:

$$\mathcal{R}_n(\mathcal{F}) \leq \frac{4L}{\sqrt{n}} + 4L\sqrt{\frac{d \log(1 + L\sqrt{n})}{n}}$$

## Examples: Nonparametric functions

### Example

Suppose  $\mathcal{F}$  is a class of  $L$  Lipschitz functions which are supported on  $[0, 1]$  and  $f(0) = 0$ . Note that  $\mathcal{F}$  is closed under negation.  $f$  is  $L$  Lipschitz i.e.  $|f(x) - f(x')| \leq L|x - x'| \forall x, x' \in [0, 1]$ .

$$\mathcal{R}_n(\mathcal{F}) = O\left(\frac{L}{n}\right)^{1/3}$$

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## Examples: Nonparametric functions

- Consider the process  $f(X_1^n) \rightarrow \langle \epsilon, f(X_1^n) \rangle = Y_f$
- $Y_f - Y_{f'} \sim$  subGaussian with var proxy  $\|f(X_1^n) - f'(X_1^n)\|_2^2$
- So  $d_Y(f, f') = \|f(X_1^n) - f'(X_1^n)\|_2 \leq \sqrt{n} \|f - f'\|_\infty$
- The diameter is  $D = \sup_{f, f' \in \mathcal{F}(X_1^n)} d_X(f, f') \leq 2L\sqrt{n}$
- So,  $N(\delta, \mathcal{F}(X_1^n), \|\cdot\|_2) \leq N(\delta/\sqrt{n}, \mathcal{F}, \|\cdot\|_\infty)$

$$\begin{aligned}
 n\mathcal{R}_n(\mathcal{F}) &\leq E\left[\sup_{f \in \mathcal{F}(X_1^n)} Y_f\right] \leq E\left[\sup_{f, f' \in \mathcal{F}(X_1^n)} (Y_f - Y_{f'})\right] \\
 &\leq 2E\left[\sup_{d_Y(f, f') \leq \delta} (Y_f - Y_{f'})\right] + 2D\sqrt{\log N(\delta/\sqrt{n}, \mathcal{F}, \|\cdot\|_\infty)} \\
 &\leq 2\delta\sqrt{n} + 4L\sqrt{n(L\sqrt{n})/\delta} \\
 &\leq 2\delta\sqrt{n} + 4L^{3/2}\sqrt{n^{3/2}/\delta}
 \end{aligned}$$

- Set  $\delta^{3/2} = CL^{3/2}n^{1/4}$ , i.e.  $\delta = C'Ln^{1/6}$  to get  $\mathcal{R}_n = O(n^{-1/3})$

# Examples: operator norm of a subgaussian matrix

## Example

Let  $W \in \mathbb{R}^{n \times d}$  be a random matrix with zero-mean i.i.d. entries  $W_{ij}$ , each sub-Gaussian with parameter  $\sigma = 1$ . Examples include the standard Gaussian ensemble  $W_{ij} \sim N(0, 1)$ , and the Rademacher ensemble  $W_{ij} \in \{-1, +1\}$  equiprobably. The operator norm of the matrix  $W$  corresponds to its maximum singular value; equivalently

$$\|W\|_{op} = \sup_{\|v\|=1, v \in \mathbb{R}^d} \|Wv\|_2$$

We will show that

$$\frac{1}{\sqrt{n}} E[\|W\|_{op}] \leq C \left( 1 + \sqrt{\frac{d}{n}} \right)$$



## Examples: operator norm of a subgaussian matrix

### Definition

Define a set of matrices:

$$M_{n,d} = \{\Theta \in \mathbb{R}^{n \times d} \mid \text{rank}(\Theta) = 1, \|\Theta\|_F = 1\}$$

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- We are going to look at operator norm as the sup of  $\langle W, \Theta \rangle$
- Then we will show that  $\langle W, \Theta \rangle$  is a subgaussian process w.r.t the Frobenius norm
- We will apply first discretization lemma.
- We will bound the covering number of  $M_{n,d}$

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- We are going to look at operator norm as the sup of  $\langle W, \Theta \rangle$
- Define by  $\mathcal{S}_{n-1}$  the set of unit vectors in  $n$  dimensions.

$$\begin{aligned}\|W\|_{op} &= \sup_{v \in \mathcal{S}_{d-1}} \|Wv\|_2 \\ &= \sup_{\substack{u \in \mathcal{S}_{n-1} \\ v \in \mathcal{S}_{d-1}}} u^T Wv \\ &= \sup_{\substack{u \in \mathcal{S}_{n-1} \\ v \in \mathcal{S}_{d-1}}} \langle W, uv^T \rangle \\ &= \sup_{\Theta \in M_{n,d}} \langle W, \Theta \rangle\end{aligned}$$

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$$\begin{aligned}\langle W, \Theta \rangle - \langle W, \Theta' \rangle &= \langle W, \Theta - \Theta' \rangle \\ &\sim \text{Subgaussian with var proxy } \|\Theta - \Theta'\|_F^2\end{aligned}$$

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$$\|W\|_{op} \leq 2E \underbrace{\left[ \sup_{\substack{\Theta, \Theta' \in M_{n,d} \\ \|\Theta - \Theta'\|_F \leq \delta}} \langle W, \Theta - \Theta' \rangle \right]}_{(A)} + 2D \sqrt{\log N(\delta, M_{n,d}, \|\cdot\|_F)}$$



## Examples: operator norm of a subgaussian matrix

- Bound part (A)

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- Bound part (A)
- Use the fact that,

$$\langle A, B \rangle \leq \sum_i \sigma_i(A) \sigma_i(B) \leq \|A\|_{op} \underbrace{\|B\|_*}_{\text{Nuclear norm}}$$

- So part A is less than

$$\begin{aligned} \sup_{\Theta \dots} (\sigma_1(\Theta - \Theta') + \sigma_2(\Theta - \Theta')) E \|W\|_{op} &\leq \sqrt{2} \|\Theta - \Theta'\|_F E [\|W\|_{op}] \\ &\leq \sqrt{2} \delta E [\|W\|_{op}] \end{aligned}$$

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- Find covering number of  $M_{n,d}$
- Use the fact that,  $M_{n,d} = \{uv^T, u \in \mathcal{S}_{n-1}, v \in \mathcal{S}_{d-1}\}$
- Now do a  $\delta/2$  cover of the unit balls in  $n$  and  $d$  dimensions.
- Let them be  $\{x_1, x_2, \dots, \}$  and  $\{y_1, y_2, \dots, \}$
- The cover of  $M_{n,d}$  can be obtained using  $u_i v_j^T$
- So, the covering number is upper bounded by  $(1 + 2/\delta)^{n+d}$

## Examples: operator norm of a subgaussian matrix

- So we have:

$$E[\|W\|_{op}] \leq 2\sqrt{2}\delta E[\|W\|_{op}] + 4\sqrt{(n+d)\log(1+2/\delta)}$$

- Make  $\delta = 1/4\sqrt{2}$  to obtain result.