

# Lecture 8 Uniform Bound

IEMS 402 Statistical Learning

Northwestern

# Ref

[https://raw.githubusercontent.com/tengyuma/cs229m\\_notes/main/master.pdf](https://raw.githubusercontent.com/tengyuma/cs229m_notes/main/master.pdf) section 4.1-4.3

<https://people.eecs.berkeley.edu/~bartlett/courses/281b-sp08/19.pdf>

<http://www.stat.yale.edu/~yw562/teaching/598/lec14.pdf>

# Uniform Bound

# Recall

$$L(\hat{\theta}) - L(\theta^*) = \underbrace{L(\hat{\theta}) - \hat{L}(\hat{\theta})}_{\textcircled{1}} + \underbrace{\hat{L}(\hat{\theta}) - \hat{L}(\theta^*)}_{\textcircled{2}} + \underbrace{\hat{L}(\theta^*) - L(\theta^*)}_{\textcircled{3}}.$$

The diagram shows the decomposition of the loss difference into three terms, labeled 1, 2, and 3. Arrows from terms 1 and 3 point to the final inequality, indicating that these terms are bounded by the supremum of the absolute difference between the true loss and the empirical loss.

$$\leq 2 \sup_{\theta \in \Theta} |L(\theta) - L(\hat{\theta})|$$

# Uniform Bound

Bound  $\sup_{\theta \in \Theta} |L(\theta) - L(\hat{\theta})|$



Why can't we use Chernoff/CLT?

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Why can't we use Chernoff/CLT?

Uniform Bound:

$$\Pr \left[ \forall \theta \in \Theta, |\hat{L}(\theta) - L(\theta)| \geq \varepsilon' \right] \leq \sum_{\theta \in \Theta} \Pr \left[ |\hat{L}(\theta) - L(\theta)| \geq \varepsilon' \right].$$

# Finite Hypothesis Class

**Theorem 4.1.** *Suppose that our hypothesis class  $\mathcal{H}$  is finite and that our loss function  $\ell$  is bounded in  $[0, 1]$ , i.e.  $0 \leq \ell((x, y), h) \leq 1$ . Then  $\forall \delta$  s.t.  $0 < \delta < \frac{1}{2}$ , with probability at least  $1 - \delta$ , we have*

$$|L(h) - \hat{L}(h)| \leq \sqrt{\frac{\ln |\mathcal{H}| + \ln(2/\delta)}{2n}} \quad \forall h \in \mathcal{H}. \quad (4.9)$$

*As a corollary, we also have*

$$L(\hat{h}) - L(h^*) \leq \sqrt{\frac{2(\ln |\mathcal{H}| + \ln(2/\delta))}{n}}. \quad (4.10)$$

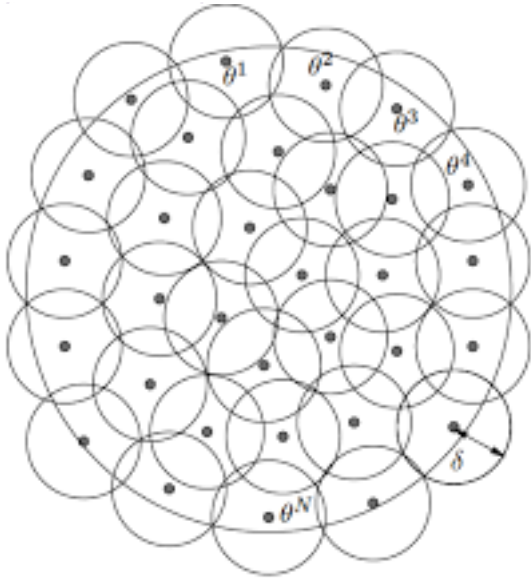
# Finite Hypothesis Class



# Infinite Hypothesis Class

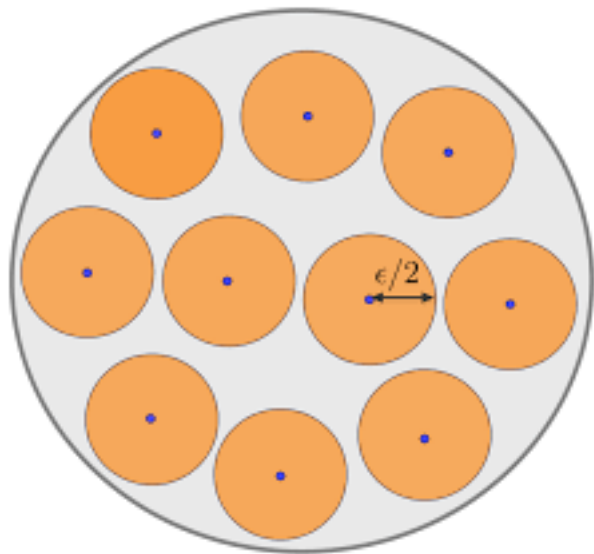
# Epsilon Cover

**Definition 14.1** ( $\epsilon$ -covering). Let  $(V, \|\cdot\|)$  be a normed space, and  $\Theta \subset V$ .  $\{V_1, \dots, V_N\}$  is an  $\epsilon$ -covering of  $\Theta$  if  $\Theta \subset \cup_{i=1}^N B(V_i, \epsilon)$ , or equivalently,  $\forall \theta \in \Theta, \exists i$  such that  $\|\theta - V_i\| \leq \epsilon$ .



# Epsilon Packing

**Definition 14.2** ( $\epsilon$ -packing). Let  $(V, \|\cdot\|)$  be a normed space, and  $\Theta \subset V$ .  $\{\theta_1, \dots, \theta_M\}$  is an  $\epsilon$ -packing of  $\Theta$  if  $\min_{i \neq j} \|\theta_i - \theta_j\| > \epsilon$  (notice the inequality is strict), or equivalently  $\bigcap_{i=1}^M B(\theta_i, \epsilon/2) = \emptyset$ .



# Covering and Packing Number

**Definition 14.3** (Covering number).  $N(\Theta, \|\cdot\|, \epsilon) := \min\{n : \exists \epsilon\text{-covering over } \Theta \text{ of size } n\}$ .

**Definition 14.4** (Packing number).  $M(\Theta, \|\cdot\|, \epsilon) := \max\{m : \exists \epsilon\text{-packing of } \Theta \text{ of size } m\}$ .

# Fact

**Theorem 14.1.** *Let  $(V, \|\cdot\|)$  be a normed space, and  $\Theta \subset V$ . Then*

$$M(\Theta, \|\cdot\|, 2\epsilon) \stackrel{(a)}{\leq} N(\Theta, \|\cdot\|, \epsilon) \stackrel{(b)}{\leq} M(\Theta, \|\cdot\|, \epsilon).$$

# Dimension Dependency

Intuition: A  $d$ -dimensional set has metric dimension  $d$ . ( $N(\epsilon) = \Theta(1/\epsilon^d)$ .)

Example:  $([0, 1]^d, l_\infty)$  has  $N(\epsilon) = \Theta(1/\epsilon^d)$ .

# Discretization Theorem

**Theorem 1.1.** Discretization Theorem:

$$\hat{R}(f) \leq \inf_{\alpha} \left( \alpha + \sqrt{\frac{2 \log N(\alpha, F, L_2(P_n))}{n}} \right)$$

# Application

**Theorem 3.3** (Subgaussian covariance concentration). *Suppose  $A \in \mathbb{R}^{d \times n}$  is a random matrix with columns  $a_i \in \mathbb{R}^d$  that are independent, zero-mean, and 1-subgaussian. Further, assume that  $\mathbb{E} \left[ \frac{1}{n} AA^\top \right] = I_d$ .*

*Then,  $\exists$  universal constant  $C > 0$  such that,  $\forall s \geq 0$ ,*

$$\Pr \left[ \left\| \frac{1}{n} AA^\top - I_d \right\|_{op} > \max(\delta, \delta^2) \right] \leq 2 \exp(-s^2), \text{ for } \delta = C \left( \sqrt{\frac{d}{n}} + \frac{s}{\sqrt{n}} \right).$$



The background of the slide features several thin, light purple lines that intersect and cross each other in various directions, creating a complex, abstract geometric pattern. The lines vary in length and orientation, some extending from the edges towards the center, while others are shorter and more localized.

# Chaining

# Dudley's Theorem

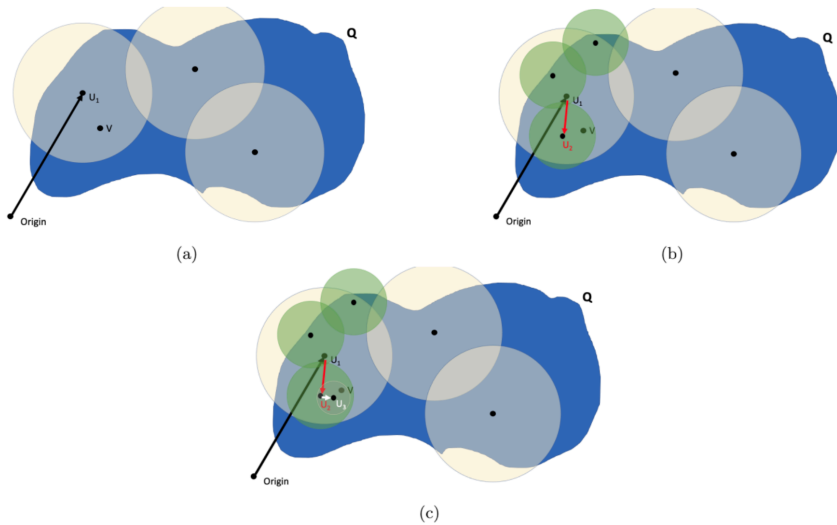
**Theorem 3.1.** Dudley:

$$\hat{R}(F) \leq 12 \int_0^\infty \frac{\log N(\epsilon, F, L_2(P_n))}{n} d\epsilon$$

# Chaining

The Chaining idea is to rewrite  $f$  as follows:

$$f = f + \sum_{i=1}^N (\hat{f}_i - \hat{f}_{i-1}) + \cancel{f_0} - \hat{f}_N.$$



# Example

**Example.**  $F =$  the non-decreasing function from  $\mathbb{R}$  to  $[0, 1]$ .

We can actually cover such a function uniformly. We only need to approximate it at  $n$  points, marked in the figure. If it is within  $\alpha$  at each of these points then the  $L_2$  distance will be no more than  $\alpha$ . From the approximating points one can produce a non-decreasing function: for each of the  $\alpha$ -levels (of which there will be  $1/\alpha$ ), just specify one of the  $n$  points at which it increases above that level. From this we can (loosely, but to the right order of magnitude) upper bound the size of the class of estimate functions:  $|\hat{F}| \leq n^{1/\alpha}$ .

We see that we can cover  $F$  in  $L_2$ :

$$N(\alpha, F, L_2(P_n)) \leq Cn^{1/\alpha}.$$

1. The Discretization Theorem gives

$$\hat{R}_n(F) \leq c \left( \frac{\log n}{n} \right)^{1/3}$$

2. The Chaining Theorem gives

$$\hat{R}_n(F) \leq 12 \int_0^1 \sqrt{\frac{\log n}{\alpha n}} d\alpha = 12 \sqrt{\frac{\log n}{n}} \int_0^1 \sqrt{\frac{1}{\alpha}} d\alpha = 24 \sqrt{\frac{\log n}{n}}$$

# Chaining