

SDS 384 11: Theoretical Statistics

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

Purnamrita Sarkar
Department of Statistics and Data Science
The University of Texas at Austin

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:

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

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

- 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 δ can be chosen to achieve the optimal trade-off between two terms.

- Choose a δ 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 $X_{\theta^1} - X_{\theta^2} \sim \text{Subgaussian}(d_X(\theta^1, \theta^2))$.

Finite class lemma for subgaussian processes

Theorem

Consider X_θ 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 λ .

Finishing the proof

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

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

Examples: 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 Θ , 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 $Y_\theta - Y_{\theta'} \sim \text{Subgaussian}(d_X(\theta, \theta'))$
- 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,

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

-

$$n\mathcal{R}_n(\mathcal{F}) \leq E \underbrace{\sup_{\substack{\|\theta - \theta'\|_2 \leq \delta \\ \theta, \theta' \in \Theta}} (Y_\theta - Y_{\theta'})}_{A} + 2D\sqrt{\log N(\delta; \mathcal{F}, d_X)}$$

- $A \leq \delta E \left[\sup_{\|v\|_2=1} \langle \epsilon, v \rangle \right] \leq \delta \sqrt{n}$
- $D = \sup_{\theta, \theta'} d_X(\theta, \theta') = 2L\sqrt{n}$

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

$$\mathcal{R}_n(\mathcal{F}) \leq \frac{2\delta}{\sqrt{n}} + 4L\sqrt{\frac{d \log(1 + L\sqrt{n}/\delta)}{n}}$$

- Setting $\delta = 1$ gives:

$$\mathcal{R}_n(\mathcal{F}) \leq \frac{2L}{\sqrt{n}} + 4L\sqrt{\frac{d \log(1 + L\sqrt{n})}{n}}$$