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Lecture 30

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Remark 1 *For more information on the topic please see Lecture notes for STAT311 by John Duchi at Stanford which was used as a reference in preparing these notes.*

The goal of this lecture is to demonstrate how lower bounds for the minimax estimator can be obtained for two simple applications.

1 Recap

We had earlier looked at the Le-Cam's Inequality in the context of simple-vs-simple hypothesis testing and its relation to Total Variation Distance and the K-L Divergence. These results have been summarized here for reference.

Theorem 1 *Le-Cam's Method - Reducing Estimation to Hypothesis Testing*

Suppose that $X_1, \ldots, X_n \sim \mathcal{P}_\theta$ for $\theta \in \Theta$ are independent and identically distributed, $\rho : \Theta \times \Theta \to \mathbb{R}_+$ is a semi-metric, and $\Phi : \mathbb{R}_+ \to \mathbb{R}_+$ is a nondecreasing function such that $\Phi(0) = 0$. Then for any $\theta_0, \theta_1 \in \Theta$ such that $\rho(\theta_0, \theta_1) > 2\delta$ then

$$\inf_{\hat{\theta}(X)} \sup_{\theta \in \Theta} \mathbb{E}_{\mathcal{P}_\theta} \left[\Phi(\rho(\hat{\theta}(X), \theta)) \right] \geq \Phi(\delta) \inf_{\Psi} \frac{1}{2} \left(\Pr(\Psi(X) \neq 0 \mid \mathcal{P}_{\theta_0}) + \Pr(\Psi(X) \neq 1 \mid \mathcal{P}_{\theta_1}) \right)$$

where the infimum is taken over all functions $\Psi : \mathcal{X} \to \{0, 1\}$.

Theorem 2 *Relating Hypothesis Test Error to Total Variation Distance*

Let $\mathcal{X}$ be an arbitrary set. For any distributions P_0 and P_1 on $\mathcal{X}$,

$$\inf_{\Psi} \{ P_0(\Psi(X) \neq 0) + P_1(\Psi(X) \neq 1) \} = 1 - ||P_0 - P_1||_{TV}$$

where the infimum is taken over all tests $\Psi : \mathcal{X} \to \{0, 1\}$

Theorem 3 *Pinkster's Inequality - Relating Total Variation Distance to K-L Divergence*

For any two distributions P_0 and P_1 on $\mathcal{X}$,

$$||P_0 - P_1||_{TV} \leq \sqrt{\frac{D_{KL}(P_0||P_1)}{2}}$$

Combining Theorems 1, 2 and 3, we can rewrite the minimax lower bound in terms of the K-L Divergence which is easier to compute.

$$\inf_{\hat{\theta}(X)} \sup_{\theta \in \Theta} \mathbb{E}_{\mathcal{P}_\theta} \left[\Phi(\rho(\hat{\theta}(X), \theta)) \right] \geq \frac{1}{2} \Phi(\delta) \left(1 - \sqrt{\frac{D_{KL}(P_0||P_1)}{2}} \right) \tag{1}$$

We also note the following property of K-L Divergence.

Lemma 4 *K-L divergence on Product Distributions*

Let P_0 and P_1 denote distributions on $\mathcal{X}$, Let P_0^n and P_1^n denote their product distributions. Then,

$$D_{KL}(P_0^n||P_1^n) = n D_{KL}(P_0||P_1)$$

2 Application 1 - Testing Normal Mean

Suppose we observe data $X_1, X_2, \ldots, X_n \sim \mathbf{N}(\mu, \sigma^2)$. We wish to estimate μ (when σ^2 is known).

2.1 Lower bound for hypothesis testing

In the simple-vs-simple hypothesis testing let the null hypothesis be $H_0 : \mu = \mu_0$ and let the alternate hypthesis be $H_1 : \mu = \mu_1$. We denote $P_0 = \mathbf{N}(\mu_0, \sigma^2)$ and $P_1 = \mathbf{N}(\mu_1, \sigma^2)$. Let P_0^n denote the product distribution over n samples iid from P_0, and let P_1^n denote the product distribution over n samples iid from P_1.

Let us first compute a lower bound on the total probability of error of hypothesis testing, which we recall from Theorem 2 and 3 that

$$\begin{aligned}\inf_{\Psi} \left(\Pr(\Psi(X) \neq 0 \mid \mu = \mu_0) + \Pr(\Psi(X) \neq 1 \mid \mu = \mu_1)\right) &= 1 - ||P_0^n - P_1^n||_{TV} \\ &\geq 1 - \sqrt{\frac{D_{KL}(P_0^n||P_1^n)}{2}}.\end{aligned}$$

The bound with respect to KL-divergence is easier to bound for product distributions than directly computing the total variation distance between product distributions. In fact, we can show that

$$D_{KL}(P_0^n||P_1^n) = nD_{KL}(P_0^n||P_1^n).$$

We can compute $D_{KL}(P_0||P_1)$ as

$$\begin{aligned}D_{KL}(P_0||P_1) &= \int \mathcal{P}_{\mu_0}(x) \log \left(\frac{P_{\mu_0}(x)}{P_{\mu_1}(x)}\right) dx \\ &= \int \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu_0)^2}{2\sigma^2}\right) \left[\frac{(\mu_1^2 - \mu_0^2)}{2\sigma^2} + \frac{2(\mu_0 - \mu_1)}{2\sigma^2}\right] dx \\ &= \frac{1}{2\sigma^2} \left(\mu_1 - \mu_0\right)^2\end{aligned}$$

Therefore, the lower bound for the total probability of error for testing between two Gaussians of mean μ_0 and μ_1 is

$$1 - \frac{|\mu_1 - \mu_0|}{2\sigma}\sqrt{n}.$$

This implies that if $n < \frac{\sigma^2}{(\mu_1 - \mu_0)^2}$, then the total probability of error for hypothesis testing must be larger than $\frac{1}{2}$.

2.2 Upper bound for hypothesis testing

Without loss of generality, assume that $\mu_0 < \mu_1$. Consider the test which rejects the null hypothesis if $\frac{1}{n} \cdot \sum_{i=1}^n X_i \geq \frac{1}{2}(\mu_1 - \mu_0)$. We can use Hoeffding's inequality to bound the total probability of error, in particular the test can only makes an error in the case that

$$\left|\frac{1}{n} \cdot \sum_{i=1}^n X_i - \mu\right| \geq \frac{1}{2}(\mu_1 - \mu_0).$$

We can bound this event using Hoeffding's inequality,

$$\mathbb{P}\left(\left|\frac{1}{n} \cdot \sum_{i=1}^n X_i - \mu\right| \geq \frac{1}{2}(\mu_1 - \mu_0)\right) \leq 2\exp\left(\frac{-n(\mu_1 - \mu_0)^2}{8\sigma^2}\right)$$

Therefore, if Ψ indicates the specific test defined above, then

$$(\Pr(\Psi(X) \neq 0 \mid \mu = \mu_0) + \Pr(\Psi(X) \neq 1 \mid \mu = \mu_1)) \leq 4 \exp\left(\frac{-n(\mu_1 - \mu_0)^2}{8\sigma^2}\right).$$

Therefore, if $n > \frac{8\ln(8)\sigma^2}{(\mu_1-\mu_0)^2}$, then the above simple test will achieve total probability of error less than $\frac{1}{2}$.

2.3 Lower bound for mean squared error in estimation

Next, suppose we would like to compute a lower bound on the minimax risk for the estimation task with respect to the squared loss (corresponding to mean squared error),

$$\inf_{\hat{\theta}(X)} \sup_{\theta \in \Theta} \mathbb{E}_{\mathcal{P}_\theta}\left[(\hat{\theta}(X) - \theta)^2\right]$$

The semi-metric is $\rho(\mu_0, \mu_1) = |\mu_0 - \mu_1|$ and the loss is $\Phi(\rho) = \rho^2$.

From equation 1 and Lemma 4, it follows that for any choice of μ_0 and μ_1 such that $|\mu_0 - \mu_1| \geq 2\delta$, the minimax estimator is lower bounded by

$$\begin{aligned}
\inf_{\hat{\theta}(X)} \sup_{\theta \in \Theta} \mathbb{E}_{\mathcal{P}_\theta}\left[\Phi(\rho(\hat{\theta}(X), \theta))\right] &\geq \frac{1}{2}\Phi(\delta)\left(1 - \sqrt{\frac{nD_{KL}(P_0||P_1)}{2}}\right) \\
&= \frac{1}{2}\delta^2\left(1 - \frac{|\mu_1 - \mu_0|}{2\sigma}\sqrt{n}\right).
\end{aligned}$$

We would like to choose δ, μ_0, and μ_1 to maximize the lower bound. For some pair of μ_0 and μ_1, the maximum delta we can choose is is $(\mu_0 - \mu_1)/2$, while still satisfying the constraint that μ_0 and μ_1 are at least 2δ distance away. By plugging this value of δ in, it follows that

$$\inf_{\hat{\theta}(X)} \sup_{\theta \in \Theta} \mathbb{E}_{\mathcal{P}_\theta}\left[\Phi(\rho(\hat{\theta}(X), \theta))\right] \geq \frac{|\mu_1 - \mu_0|^2}{8}\left(1 - \frac{|\mu_1 - \mu_0|}{2\sigma}\sqrt{n}\right)$$

Finally we want to choose the value of μ_0 and μ_1 again to maximize the lower bound. If we differentiate the right hand side wrt $|\mu_1 - \mu_0|$, we get

$$\frac{|\mu_1 - \mu_0|}{4} - \frac{3|\mu_1 - \mu_0|^2}{16\sigma}\sqrt{n}.$$

The stationary point at $|\mu_1 - \mu_0| = 0$ is a minimum (when plugged in, we get a meaningless lower bound of 0). We can show the lower bound is maximized at the other stationary point

$$|\mu_1 - \mu_0| = \frac{4\sigma}{3\sqrt{n}}.$$

Hence by plugging in this value for $|\mu_1 - \mu_0|$, we can show that

$$\inf_{\hat{\theta}(X)} \sup_{\theta \in \Theta} \mathbb{E}_{\mathcal{P}_\theta}\left[\Phi(\rho(\hat{\theta}(X), \theta))\right] \geq \frac{1}{8}\left(\frac{4\sigma}{3\sqrt{n}}\right)^2\left(1 - \frac{2}{3}\right) = \frac{1}{8} \cdot \frac{16\sigma^2}{9n} \cdot \frac{1}{3} = \frac{2\sigma^2}{27n}$$

2.4 Upper bound for estimation

Consider the simple estimator $\hat{\mu} := \frac{1}{n} \cdot \sum_{i=1}^{n} X_i$. We can show an upper bound on the worst case mean-squared error using Hoeffding's Inequality.

$$\begin{aligned}
\mathbb{E}[(\hat{\mu} - \mu)^2] &= \int_0^\infty \mathbb{P}\left((\hat{\mu} - \mu)^2 > t\right) dt \\
&\leq \int_0^\infty 2\exp\left(\frac{-nt}{2\sigma^2}\right) dt \\
&= 2\left(\frac{-2\sigma^2}{n}\right) \exp\left(\frac{-nt}{2\sigma^2}\right)\Big|_0^\infty \\
&= \frac{4\sigma^2}{n}
\end{aligned}$$

Thus the sample mean estimator cannot do worse than $\frac{4\sigma^2}{n}$ and no estimator can do better than $\frac{2\sigma^2}{27n}$.

3 Application 2 - Kernel Regression

In Kernel Regression we observe data $Y_i = f(X_i) + \epsilon_i$ where X_i is a known feature matrix and the errors/noise are iid mean-zero Gaussian $\epsilon_i \sim \mathbf{N}(0,1)$.

We wish to estimate the function f under the assumption that it is Lipschitz continuous (with constant L).

The **Nadaraya-Watson Estimator** for fixed x_0 is

$$\hat{f}(x) = \frac{\sum_{i=1}^n K(x_i, x) Y_i}{\sum_{i=1}^n K(x_i, x)}$$

for some choice of kernel function K. We showed in lecture 19 that for a specific kernel function $K()$, some constant c and fixed x_0,

$$\sup_{f \text{ is L-Lipschitz}} \mathbb{E}\left[(\hat{f}(x_0) - f(x_0))^2\right] \leq c\left(\frac{L\sigma^2}{n}\right)^{\frac{2}{3}}$$

We will now show a lower bound on the MSE. We choose the loss and the semi-metric according to

$$\Phi(\rho) = \rho^2, \quad \rho(f_0, f_1) = |f_0(x_0) - f_1(x_0)| \quad (\text{ distance at } x_0).$$

We choose the two functions to test on as $f_0(x) = 0$ for all x and

$$f_1(x) = \begin{cases} L(\epsilon - |x - x_0|) & \forall\, |x - x_0| \leq \epsilon \\ 0 & \text{otherwise.} \end{cases}$$

Note that $\rho(f_0, f_1) = L\epsilon$. Corresponding to f_0 and f_1, we have the two distributions

$$P_0\left(\begin{bmatrix} Y_1 \\ \vdots \\ Y_n \end{bmatrix} \mid f = f_0\right) \sim \mathbf{N}\left(\begin{bmatrix} f_0(X_1) \\ \vdots \\ f_0(X_n) \end{bmatrix}, \sigma^2\mathbf{I}\right) = \mathbf{N}\left(\mathbf{0}, \sigma^2\mathbf{I}\right) \quad \text{and} \quad P_1\left(\begin{bmatrix} Y_1 \\ \vdots \\ Y_n \end{bmatrix} \mid f = f_1\right) \sim \mathbf{N}\left(\begin{bmatrix} f_1(X_1) \\ \vdots \\ f_1(X_n) \end{bmatrix}, \sigma^2\mathbf{I}\right)$$

So to obtain a lower bound we need to compute the KL divergence of these two multivariate gaussian distributions.

$$
\begin{aligned}
D_{KL}\left(\mathbf{N}(\mu_0,\sigma^2\mathbf{I})\|\mathbf{N}(\mu_0,\sigma^2\mathbf{I})\right) &= \int P_0(\vec{Y})\log\left(\frac{P_0(\vec{Y})}{P_1(\vec{Y})}\right)d\vec{Y}\\
&= \int \Pi_{i=0}^{n} P_{0i}(Y_i)\log\left(\frac{\Pi_{i=0}^{n} P_{0i}(Y_i)}{\Pi_{i=0}^{n} P_{1i}(Y_i)}\right)d\vec{Y}\\
&= \sum_{i=0}^{n}\int \log\left(\frac{P_{0i}(Y_i)}{P_{1i}(Y_i)}\right)P_{0i}(Y_i)dY_i\cdot\left(\underbrace{\Pi_{j\neq i}P_{0j}\left(Y_j\right)dY_j}_{\text{integrates to one}}\right)\\
&= \sum_{i=0}^{n}\int \log\left(\frac{P_{0i}(Y_i)}{P_{1i}(Y_i)}\right)P_{0i}(Y_i)dY_i \quad \equiv \text{KL divergence of normal distributions}\\
&= \sum_{i=0}^{n}\frac{1}{2\sigma^2}\left(f_0(X_i)-f_1(X_i)\right)^2\\
&= \sum_{i=0}^{n}\mathbf{1}\{|X_i-x_0|<\epsilon\}\cdot\frac{L^2(\epsilon-|X_i-x_0|)^2}{2\sigma^2}\\
&= \frac{L^2}{2\sigma^2}\cdot 2\sum_{i=0}^{\epsilon n}\left(\frac{i}{n}\right)^2 \qquad \text{assuming that } X_i=\frac{i}{n} \text{ and } x_0,\epsilon \text{ are both multiples of } \frac{1}{n}\\
&= \frac{L^2}{\sigma^2 n^2}\cdot\left[\frac{\epsilon n(\epsilon n+1)(2\epsilon n+1)}{6}\right]\\
&\approx \frac{L^2}{\sigma^2 n^2}\cdot\frac{\epsilon^3 n^3}{3}.
\end{aligned}
$$

We made an assumption above that x_0, ϵ are multiples of $\frac{1}{n}$, but even if they were not the above bound would have same asymptotic dependence but just differ in the constant.

Therefore the minimax lower bound is

$$
\begin{aligned}
\inf_{\hat{\theta}(X)}\sup_{\theta\in\Theta}\mathbb{E}_{\mathcal{P}_\theta}\left[\Phi(\rho(\hat{\theta}(X),\theta))\right] &\geq \frac{1}{2}\Phi(\rho)\cdot\left(1-\sqrt{\frac{1}{2}D_{KL}(P_0\|P_1)}\right)\\
&\approx \frac{1}{2}\left(\frac{L\epsilon}{2}\right)^2\cdot\left(1-\sqrt{\frac{L^2\epsilon^3 n}{6\sigma^2}}\right).
\end{aligned}
$$

By differentiating the right hand side wrt ϵ and equating to zero we can see that the lower bound is maximized at

$$
\epsilon = \Theta\left(\left(\frac{\sigma}{L\sqrt{n}}\right)^{\frac{2}{3}}\right).
$$

By plugging in this value of ϵ, we show that the minimax lower bound is

$$
\inf_{\hat{\theta}(X)}\sup_{\theta\in\Theta}\mathbb{E}_{\mathcal{P}_\theta}\left[\Phi(\rho(\hat{\theta}(X),\theta))\right] = \Omega\left(\left(\frac{L\sigma^2}{n}\right)^{\frac{2}{3}}\right),
$$

matching our upper bound up to a constant.