STATS300B – Lecture 7

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Contents

1 Motivation

1. We want to prove consistency of the MLE.
2. The MLE maximizes the log-likelihood which is an empirical average. In particular, the log-likelihood is a random function.
3. We will thus use the weak law for random functions.

2 Random functions

Recall the following,

Theorem 1. *Let K be a compact set and suppose $X_1, X_2, \ldots$ are i.i.d. and $W_i(t) = h(t, X_i) \in C(K)$ for all values of X_i. Let $\mu(t) = \mathbb{E}[W_1(t)]$ and assume that $\mathbb{E}[\|W\|_\infty] < \infty$, then $\left\|\bar{W}_n - \mu\right\|_\infty \xrightarrow{p} 0$.*

We will also use the following theorem about the optimizers of random functions.

Theorem 2. *Let G_n be random functions in $C(K)$ where K is compact. Let $g \in C(K)$ be a deterministic function. Suppose that $\|G_n - g\|_\infty \xrightarrow{p} 0$, then*

1. *If $t_n \xrightarrow{p} t^*$, then $G_n(t_n) \xrightarrow{p} g(t^*)$.*
2. *Let t_n be a random variable maximizing G_n. If g achieves its maximum at a unique value t^*, then $t_n \xrightarrow{p} t^*$.*
3. *Suppose that $K \subseteq \mathbb{R}$ and t_n is a random variable solving $G_n(t_n) = 0$. If t^* is the unique value in K such that $g(t^*) = 0$, then $t_n \xrightarrow{p} t^*$.*

3 Kullback–Leibler information

Definition 1. Let P and Q be probability measures with densities p and q with respect to a common σ-finite measure μ. The *Kullback–Leibler information* of P and Q is defined to be,

$$K(P,Q) = \mathbb{E}_P\left[\log\left(\frac{p(X)}{q(X)}\right)\right].$$

Proposition 1. *For all probability distributions, $K(P,Q) \geq 0$ and $K(P,Q) = 0$ if and only if $P = Q$.*

Proof. Recall that $-\log$ is convex. Thus, by Jensen's inequality,

$$\begin{aligned}
\mathbb{E}_P\left[\log\left(\frac{p(X)}{q(X)}\right)\right] &= \mathbb{E}_P\left[-\log\left(\frac{q(X)}{p(X)}\right)\right] \\
&\geq -\log\left(\mathbb{E}_P\left[\frac{q(X)}{p(X)}\right]\right) \\
&= -\log\left(\int_{p(x)\neq 0} q(x)dx\right) \\
&\geq -\log(1) \\
&= 0.
\end{aligned}$$

Furthermore, we have equality when $\frac{q(X)}{p(X)}$ is constant P-almost everywhere. But since p and q are densities this happens only when $P = Q$. □

Kullback–Leibler distant relates to the log-likelihood in the following way,

Lemma 1. *Consider a model $\mathcal{P} = \{P_\theta : \theta \in \Omega\}$ and consider the following assumptions,*

1. *If $\theta \neq \theta^*$, then $P_\theta \neq P_{\theta^*}$.*
2. *There exists a measure μ such that for every θ, P_θ has a density p_θ with respect to μ.*
3. *The support of P_θ, $\{x : p_\theta(x) > 0\}$ does not depend on θ.*

Then, if $X_1, \ldots, X_n$ are i.i.d. P_{θ^*}, then

$$\frac{1}{n}\left[\frac{L_n(\theta^*)}{L_n(\theta)}\right] \xrightarrow{a.s.} K(P_{\theta^*}, P_\theta),$$

where $L_n(\theta)$ is the log-likelihood evaluated at θ. In particular, for all $\theta \neq \theta^*$,

$$\mathbb{P}(L_n(\theta^*|X) \geq L_n(\theta|X)) \to 1.$$

Proof. The proof is a simple application of the strong law of large numbers. □

We are now ready to state the consistency theorem for the MLE.

Theorem 3. *Suppose that the three assumption of the previous lemma hold and that Ω is compact. Fix $\theta^* \in \Omega$ and define $h : \Omega \times \mathcal{X} \to \mathbb{R}$ as the function,*

$$h(\theta, x) = \log\left[\frac{p_\theta(X)}{p_{\theta^*}(x)}\right].$$

Let $X_0, X_1, X_2, \ldots$ be i.i.d. samples from P_{θ^*} and define $W_i(\theta) = h(\theta, X_i)$. Suppose that h is continuous in θ for every x and,

$$\mathbb{E}_{\theta^*}[\|W_0\|_\infty] < \infty.$$

Define $\widehat{\theta}_n$ to be the MLE given $X_1, \ldots, X_n$. Then, under P_{θ^*}, $\widehat{\theta}_n \xrightarrow{p} \theta$.

4 Asymptotic normality

We now know that the MLE is consistent, but what can we say about the limiting distribution?

Theorem 4. *Let $\mathcal{P} = \{P_\theta : \theta \in \Omega\}$ be a model for $X \in \mathcal{X}$. Suppose that $\Omega \subseteq \mathbb{R}$ and that P_θ has a density p_θ with respect to a common base measure μ. Suppose that the following hold,*

1. *The support of p_θ does not depend on θ.*
2. *For every $x \in \mathcal{X}$, $\frac{\partial^2}{\partial\theta^2} p_\theta(x)$ exists and is continuous in θ.*
3. *If $l(\theta) = \log p_\theta(x)$, then the Fisher information exists, is finite and can be calculated as either*
$$I(\theta) = \mathbb{E}_\theta\left[\left(\frac{\partial}{\partial\theta} l(\theta)\right)^2\right] \quad \textit{or} \quad I(\theta) = -\mathbb{E}_\theta\left[\frac{\partial^2}{\partial\theta^2} l(\theta)\right],$$
and $\mathbb{E}\left[\frac{\partial}{\partial\theta} l(\theta)\right] = 0$.
4. *For every θ in the interior of Ω, there exists $\varepsilon > 0$ such that $\mathbb{E}_\theta \left\| \mathbf{1}_{[\theta-\varepsilon, \theta+\varepsilon]} \frac{\partial^2}{\partial\theta^2} l(\theta) \right\| < \infty$.*
5. *The MLE $\widehat{\theta}_n$ is consistent.*

Then for any θ^* in the interior of Ω, if $X_i \overset{\text{iid}}{\sim} P_{\theta^*}$, then
$$\sqrt{n}\left(\widehat{\theta}_n - \theta\right) \xrightarrow{d} \mathsf{N}\left(0, \frac{1}{I(\theta)}\right).$$