STAT 543/641 – Winter 2019 – Homework #2

Due Wednesday, March 20, 2019

Notation: Suppose $(x_1, y_1, \ldots, (x_n, y_n) \in \mathbb{R} \times \{0, 1\}$. Set

$$\sigma(t) = \frac{1}{1 + e^{-t}}$$

$$p_i(a, b) = \sigma(a + bx_i)^{y_i} \big(1 - \sigma(a + bx_i)\big)^{1 - y_i}$$

$$\begin{aligned} \ell_i(a, b) &= -\log p_i(a, b) \\ &= -y_i \log \sigma(a + bx_i) - (1 - y_i) \log \big(1 - \sigma(a + bx_i)\big) \end{aligned}$$

$$\ell(a, b) = \sum_{i=1}^{n} \ell_i(a, b)$$

1. In this problem, we establish a sufficient condition for the uniqueness of maximum likelihood estimates for univariate logistic regression coefficients, assuming such estimates exist.

   (a) Prove:

   $$\sigma'(x) = \sigma(x)\big(1 - \sigma(x)\big) \tag{$*$}$$

   Conclude that $\sigma'(x) > 0$ for all x.

   (b) Prove that

   $$\nabla \ell_i(a, b) = (y_i - \sigma(a + bx_i)) \begin{bmatrix} 1 \\ x_i \end{bmatrix} \qquad \text{(Hint: Use } (*).)$$

   and that

   $$\nabla^2 \ell_i(a, b) = -\sigma'(a + bx_i) \begin{bmatrix} 1 & x_i \\ x_i & x_i^2 \end{bmatrix}.$$

   Deduce that $\nabla^2 g(a, b)$ is positive-semidefinite but not positive-definite, making $g(a, b)$ convex but not strictly convex.

(c) Find a basis of the nullspace $N(\nabla^2 \ell_i(a,b))$ of $\nabla^2 \ell_i(a,b)$ whose elements do not depend on a and b.

(d) Suppose that there are indices i and j such that $x_i \neq x_j$. Prove that

$$\bigcap_{i=1}^{n} N(\nabla^2 \ell_i(a,b)) = \left\{ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right\}.$$

(Hint: Use (4).)

(e) Suppose that there are indices i and j such that $x_i \neq x_j$. Show that $\nabla^2 \ell(a,b)$ is positive-definite and, hence, that $\ell(a,b)$ is strictly convex.

(f) Conclude that if that there are indices i and j such that $x_i \neq x_j$, then maximum likelihood estimates for $\widehat{a}$ and $\widehat{b}$ are unique if they exist.

2. In this problem, we establish a sufficient condition for the existence of maximum likelihood estimates for univariate logistic regression coefficients.

Consider fitting a univariate logistic regression model to a dataset $(x_1, y_1), \ldots, (x_n, y_n)$ satisfying

$$x_1 < x_2 < \cdots < x_n.$$

(a) Prove that $\ell_i(a,b) > 0$ for all $(a,b) \in \mathbb{R}^2$.

(b) Let

$$H_i = \left\{ \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \in \mathbb{R}^2 : \lim_{t \to \infty} \ell_i(tv_1, tv_2) = \infty \right\}$$

Find a vector $\boldsymbol{w} \in \mathbb{R}^2$ such that $H_i = H(\boldsymbol{w}_i)$, where

$$H(\boldsymbol{w}_i) = \left\{ \boldsymbol{v} \in \mathbb{R}^2 : \boldsymbol{v} \cdot \boldsymbol{w}_i > 0 \right\}.$$

(c) Let $\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{w} \in \mathbb{R}^2 - \{\mathbf{0}\}$. Show that

$$H(\boldsymbol{u}) \cup H(\boldsymbol{v}) \cup H(\boldsymbol{w}) = \mathbb{R}^2 - \{\mathbf{0}\}$$

if abd only there are $a, b > 0$ such that $-\boldsymbol{u} = a\boldsymbol{v} + v\boldsymbol{w}$.

(d) Consider the following condition on a triple of indices (i,j,k):

$$y_i = y_k = 0 \text{ and } y_j = 1 \qquad \textit{or} \qquad y_i = y_k = 1 \text{ and } y_j = 0 \tag{†}$$

Suppose $1 \leq i < j < k \leq n$. Prove that (i,j,k) satisfies (†) if and only if

$$H_i \cup H_j \cup H_k = \mathbb{R}^2 - \{\mathbf{0}\}.$$

(e) Suppose that (i, j, k) is an increasing sequence of indices that satisfies (†). Prove that, for all $K > 0$, the set

$$S_K := \{(a, b) : \ell(a, b) \leq K\}$$

contains no ray from the origin, i.e., no set of the form $\{t\boldsymbol{v} : t \geq 0\}$ where $\boldsymbol{v} \in \mathbb{R}^2 - \{\mathbf{0}\}$.

(f) Use the following facts to deduce that S_K is bounded for all $K > 0$. S_K is evidently closed, so it's compact.

i. If $f : \mathbb{R}^n \to \mathbb{R}$ is a convex function, then $\{\boldsymbol{x} \in \mathbb{R}^n : f(\boldsymbol{x})| \leq K\}$ is a convex set.

ii. If C is a convex set that contains no ray, then C is bounded.

(g) Let $K > 0$ be such that S_K is nonempty and let

$$m = \inf_{(a,b)\in S_K} \ell(a, b).$$

Explain why there exists a point $(\widehat{a}, \widehat{b}) \in S_K$ such that $\ell(\widehat{a}, \widehat{b}) = m$ and why m is, in fact, the global minimum of ℓ.

(h) Prove that $(\widehat{a}, \widehat{b})$ is the unique point at which ℓ takes on its minimum value.

3. Let $X_1, \ldots, X_m$ and $Y_1, \ldots, Y_n$ be random samples from normally distributed populations with means μ_X and μ_Y and variances σ_X^2 and σ_Y^2, respectively. Let S_X^2 and S_Y^2 be the standard unbiased estimators of σ_X^2 and σ_Y^2, respectively.

(a) Suppose $\sigma_X^2 = \sigma_Y^2$ and write σ^2 for this common value.

$$S^2 := \frac{(m-1)S_X^2 + (n-1)S_Y^2}{m+n-2}$$

is an unbiased estimator of σ^2. It's called the *pooled variance estimator*.

(b) Suppose, in addition to having common variance, that the X_i are independent of the Y_i. What is the distribution of

$$\frac{(m+n-2)S^2}{\sigma^2}?$$

What is the variance of S^2?

(c) (Do not hand in.) Generalize these results from the case of $K = 2$ populations to that of an arbitrary K. Compare with equation (4.15) in [1].

(d) (Do not hand in.) Can you prove analogous results with covariance matrices in place of scalar variances?

4. Applied problem to be added...

References

[1] Gareth James, Daniela Witten, Trevor Hastie, and Robert Tibshirani, *Introduction to Statistical Learning Theory with Applications in R*, http://www-bcf.usc.edu/~gareth/ISL/.