Statistics 583, Problem Set 8 Solutions

Wellner; 5/23/2007

1. (a) Read Wasserman, section 3.4, pages 32 - 34. Then form confidence intervals for the skewness of the nerve data by all the methods discussed by Wasserman, section 3.4, pages 32 - 35 to see if you get results comparable to those in his table in example 3.17, page 34.

   (b) Form a 95% confidence interval for the skewness parameter assuming that the nerve data can be modeled by a Weibull distribution with parameters (α, β). (That is, regard $T(P) = E_P(X - \mu(P))^3/\sigma^3(P)$ as a parametric function $g(\alpha, \beta) = T(P_{\alpha,\beta})$ for $P_{\alpha,\beta}$ a Weibull distribution on $\mathbb{R}^+$, and form a confidence interval for $g(\alpha, \beta)$ via the (parametric-) delta method. Does the resulting confidence interval include 2?

   Solution (a): (i) normal bootstrap interval: based on the bootstrap standard error estimate from problem set #7 of $\hat{se}_{boot} = .163$, I get the 95% confidence interval $1.7612 \pm 1.96 * .163 = (1.442, 2.081)$.
   (ii) Percentile interval: as noted by Wasserman on page 34, this is just the interval $(\theta^*_{(B\alpha/2)}, \theta^*_{B(1-\alpha/2)})$. When I compute with $B = 10^4$ I get $(\theta^*_{(B\alpha/2)}, \theta^*_{B(1-\alpha/2)}) = (1.435, 2.064)$.
   (iii) Pivotal interval: as argued on Wasserman's pages 32 and 33 this interval is given by $(2\hat{\theta}_n - \theta^*_{(B(1-\alpha)/2)}, 2\hat{\theta}_n - \theta^*_{(B\alpha/2)}$. When I compute I get $(1.459, 2.088)$.
   (iv) Studentized interval: this is the most computationally involved of these intervals. I proceeded as suggested in Wasserman, page 35, using the (corrected version of the) non-parametric delta method applied to the bootstrap samples. When I compute with $B = 10^4$ I get $(\hat{\theta} - z^*_{1-\alpha/2}\hat{se}_{boot}, \hat{\theta} - z^*_{\alpha/2}\hat{se}_{boot}) = (1.517, 2.281)$ where $z^*_{1-\alpha/2}$ =the α sample quantile of $Z^*_1, \ldots, Z^*_B$ and $Z^*_b \equiv (\hat{\theta}^*_b - \hat{\theta})/\hat{se}^*_b$. Here is a summary table:

method	(lower bound ,upper bound)
Normal	(1.442, 2.081)
percentile	(1.435, 2.064)
pivotal	(1.459, 2.088)
studentized pivotal	(1.517 , 2.281)

   These seem to be in reasonably good agreement with the intervals obtained by Wasserman.

Solution (b): First note that

$$g(\alpha,\beta) = \frac{2\Gamma(1+1/\beta)^3 - 3\Gamma(1+1/\beta)\Gamma(1+2/\beta) + \Gamma(1+3/\beta)}{\Gamma(1+2/\beta) - \Gamma(1+1/\beta)^2}$$

is a function only of β, say $g(\beta)$. Furthermore, from our results in Stat 581,

$$\sqrt{n}(\hat{\beta}_n - \beta) \to_d N(0, \beta^2 6/\pi^2),$$

and hence, by the delta-method,

$$\sqrt{n}(g(\hat{\beta}_n) - g(\beta)) \to_d g'(\beta) N(0, \beta^2 6/\pi^2).$$

Thus a 95% parametric (model - based) confidence interval for the skewness of the nerve data is given by

$$\begin{aligned} & g(\hat{\beta}) \pm z_{.975}\sqrt{\frac{6\hat{\beta}^2[g'(\hat{\beta})]^2}{\pi^2 n}} \\ = \; & 1.77782 \pm 1.96 \cdot \frac{1.77782 \cdot 2.46058 \cdot \sqrt{6}}{\pi\sqrt{799}} \\ = \; & 1.77782 \pm 1.06 \cdot 0.0734 \\ = \; & (1.634, 1.922) \end{aligned}$$

which excludes the value 2 (the skewness of all exponential distributions), and is considerably shorter than the nonparametric CI's found in problem 1.

2. Wasserman, problem 12, page 41: Suppose that 50 people are given a placebo and 50 are given a new treatment. Thirty placebo patients show improvement, while 40 treated patients show improvement. Let $\tau = p_2 - p_1$ where p_2 is the probability of improving under treatment and p_1 is the probability of improving under placebo.
(a) Find the MLE of τ. Find the standard error and 90% confidence interval using the delta method.
(b) Find the standard error and 90% confidence interval using the bootstrap.

Solution: (a) Here $X \equiv$ number of patients showing improvement on the placebo, so $X \sim$ Binomial(m, p_1) with $m = 50$, and $Y \equiv$ number of patients showing improvement on the treatment, so $Y \sim$ Binomial(n, p_2) with $n = 50$. The MLE of $\tau = p_2 - p_1$ is simply $\hat{\tau} = \hat{p}_2 - \hat{p}_1 = Y/n - X/m = 4/5 - 3/5 = 1/5 = .20$. Furthermore, if $\lambda_N \equiv m/N \to \lambda \in [0,1]$, then

$$\begin{aligned} \sqrt{\frac{mn}{N}}(\hat{\tau} - \tau) &= \sqrt{m/N}\sqrt{n}(\hat{p}_2 - p_2) - \sqrt{n/N}\sqrt{m}(\hat{p}_1 - p_1) \\ &\to_d \sqrt{\lambda} Z_2 - \sqrt{1-\lambda} Z_1 \\ &\sim N(0, \lambda p_2 q_2 + (1-\lambda) p_1 q_1). \end{aligned}$$

Thus the standard error of $\hat{\tau}$ is

$$\begin{aligned}
\sqrt{\frac{(m/N)\hat{p}_2\hat{q}_2 + (n/N)\hat{p}_1\hat{q}_1}{mn/N}} &= \sqrt{\frac{\hat{p}_2\hat{q}_2}{n} + \frac{\hat{p}_1\hat{q}_1}{m}} \\
&= \sqrt{\frac{(4/5)(1/5)}{50} + \frac{(3/5)(2/5)}{50}} \\
&= \sqrt{\frac{10}{25\cdot 50}} = \sqrt{\frac{1}{125}} = 0.0894427,
\end{aligned}$$

and a 90% confidence interval for τ is given by

$$\begin{aligned}
&\hat{\tau} \pm z_{.05}\sqrt{\frac{\hat{p}_2\hat{q}_2}{n} + \frac{\hat{p}_1\hat{q}_1}{m}} \\
&= \frac{1}{5} \pm 1.645(0.0894427) = .20 \pm 0.147 = (0.053, 0.347).
\end{aligned}$$

3. (Bootstrapping a linear regression model a simple way.) Consider bootstrapping a linear regression model

$$Y_i = \mathbf{x}_i^T\beta + \epsilon_i, \qquad i = 1, \ldots, n$$

where the ϵ_i are i.i.d. mean 0, finite variance, and the $\mathbf{x}_i$ are given $p-$dimensional vectors, such that there is no constant term in the regression.
(a) Show that the estimated residuals $\hat{\epsilon}^T = (\hat{\epsilon}_1, \ldots, \hat{\epsilon}_n)$ satisfy $\hat{\epsilon} - \epsilon = -H\epsilon$ where $H = \mathbf{X}(\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T$ is the "hat matrix" (i.e. the projection matrix onto the column space of $\mathbf{X}$).
(b) Suppose that $\hat{\epsilon}_1^*, \ldots, \hat{\epsilon}_n^*$ is a bootstrap sample (with replacement) from $\{\hat{\epsilon}_1, \ldots, \hat{\epsilon}_n\}$. Show that

$$E_*(n^{1/2}(\hat{\beta}^* - \hat{\beta})) = (\frac{1}{n}\mathbf{X}^T\mathbf{X})^{-1}(\frac{1}{n}\mathbf{X}^T\mathbf{1})Z_n$$

where $Z_n = n^{-1/2}\sum_{i=1}^n \hat{\epsilon}_i$.
(c) Show that if $\max_{1\le i\le n} h_{ii} \to 0$, and $n^{-1}\mathbf{X}^T\mathbf{X} \to V$, a positive definite matrix, then

$$\sqrt{n}(\hat{\beta} - \beta) \to_d N_p(0, \sigma^2 V^{-1})$$

[This is a variant of the result we established in 581 via the Lindeberg - Feller CLT.]
(d). Find the mean and variance of Z_n.

(e) Suppose that:

(i) $n^{-1}\mathbf{X}^T\mathbf{X} \to V$, a positive definite matrix;

(ii) $\mathbf{X}^T\mathbf{1}/n \to \mathbf{h}$ with $\mathbf{h}^T V^{-1}\mathbf{h} < 1$;

(iii) $\max_{1\le i\le n} h_{ii} \to 0$ where h_{ii} are the diagonal elements of the hat matrix H.

Show that if (i) - (iii) hold, then the bootstrap fails in the sense that the random variable Z_n in (b) converges in distribution to a proper random variable rather than to zero.
Hint: show that (iii) implies that $\max_{1\le i\le n}|c_{ni}| \to 0$ where $\mathbf{c} = n^{-1/2}(I-H)\mathbf{1}$.

Solution: (a) Now $\hat{Y} = X\hat{\beta} = X(X^TX)^{-1}X^TY = HY$, so $\underline{\hat{\epsilon}} = Y - \hat{Y} = (I-H)Y$, and

$$\begin{aligned}\underline{\hat{\epsilon}} - \underline{\epsilon} &= (I-H)Y - (Y - X\underline{\beta}) \\ &= -H(X\underline{\beta} + \underline{\epsilon}) + X\underline{\beta} = -H\underline{\epsilon}\end{aligned}$$

since $H(X\underline{\beta}) = X\underline{\beta}$ (since $X\underline{\beta}$ is already in the column space of X!)
(b). Let $\underline{\hat{\epsilon}_i^*}$ be a sample with replacement from $\{\hat{\epsilon}_i : i = 1,\ldots,n\}$, and let $Y_i^* = x_i\hat{\beta} + \hat{\epsilon}_i$, $i = 1,\ldots,n$. Thus in vector notation, $Y^* = X\underline{\hat{\beta}} + \underline{\hat{\epsilon}}^*$ and

$$\begin{aligned}\underline{\hat{\beta}}^* &= (X^TX)^{-1}X^TY^* = (X^TX)^{-1}X^T(X\underline{\hat{\beta}} + \underline{\hat{\epsilon}}^*) \\ &= \underline{\hat{\beta}} + (X^TX)^{-1}X^T\underline{\hat{\epsilon}}^*.\end{aligned}$$

Thus

$$\sqrt{n}(\underline{\hat{\beta}}^* - \underline{\hat{\beta}}) = (n^{-1}X^TX)^{-1}(n^{-1}X^T)\sqrt{n}\underline{\hat{\epsilon}}^*,$$

and, since $E_*(\hat{\epsilon}_i^*) = n^{-1}\sum_{i=1}^n \hat{\epsilon}_i$ the expected value is

$$\begin{aligned}E_*(\sqrt{n}(\underline{\hat{\beta}}^* - \underline{\hat{\beta}}) &= (n^{-1}X^TX)^{-1}(n^{-1}X^T)\underline{1}n^{-1/2}\sum_{i=1}^n \hat{\epsilon}_i \\ &= (n^{-1}X^TX)^{-1}(n^{-1}X^T)\underline{1}Z_n.\end{aligned}$$

(c). To show that

$$\sqrt{n}(\underline{\hat{\beta}} - \underline{\beta}) \to_d N_p(0, \sigma^2 V^{-1})$$

first write $\sqrt{n}(\underline{\hat{\beta}} - \underline{\beta}) = \sqrt{n}(X^TX)^{-1}X^T\underline{\epsilon}$ so that, for any fixed vector $\lambda \in \mathbb{R}^p$,

$$\underline{\lambda}^T\sqrt{n}(\hat{\beta} - \beta) = \sqrt{n}\underline{\lambda}^T(X^TX)^{-1}X^T\underline{\epsilon} \equiv \sum_{i=1}^n a_{ni}\epsilon_i \equiv \sum_{i=1}^n X_{n,i}$$

where the vector $a_n \equiv \sqrt{n} X (X^T X)^{-1} \underline{\lambda}$. Hence we have $EX_{ni} = 0$, $Var(X_{ni}) = a_{ni}^2 \sigma^2$, and

$$\begin{aligned} \sigma_n^2 &\equiv \sum_{i=1}^n \sigma_{ni}^2 = \sigma^2 |\underline{a}|^2 \\ &= \sigma^2 n \underline{\lambda}^T (X^T X)^{-1} \underline{\lambda} \\ &\to \sigma^2 \underline{\lambda}^T V^{-1} \underline{\lambda} > 0 \end{aligned}$$

since V is positive definite.

To check the Lindeberg condition, write

$$\begin{aligned} &\frac{1}{\sigma_n^2} \sum_{i=1}^n E\{|X_{ni}|^2 1_{[|X_{ni}| > \epsilon \sigma_n]}\} \\ &= \frac{1}{\sigma_n^2} \sum_{i=1}^n a_{ni}^2 E\{\epsilon_1^2 1_{[|\epsilon_1| > \epsilon \sigma_n / |a_{ni}|]}\} \\ &\le \frac{1}{\sigma^2} E\{\epsilon_1^2 1_{[|\epsilon_1| > \epsilon \sigma_n / \max_i |a_{ni}|]}\} \\ &\to 0 \qquad \text{by the DCT since } \ E(\epsilon^2) < \infty \end{aligned}$$

if $\max_{1 \le i \le n} |a_{ni}|^2 \to 0$. But we can write $a_{ni} = \sqrt{n} \underline{x}_i^T (X^T X)^{-1} \underline{\lambda}$, so that, by Cauchy - Schwarz,

$$\begin{aligned} \max_{1 \le i \le n} |a_{ni}|^2 &\le n \max_{1 \le i \le n} (\underline{x}_i^T (X^T X)^{-1} \underline{x}_i)(\underline{\lambda}^T (X^T X)^{-1} \underline{\lambda}) \\ &= \max_{1 \le i \le n} h_{ii} \underline{\lambda}^T (n^{-1} X^T X)^{-1} \to \ 0 \cdot \underline{\lambda}^T V^{-1} \underline{\lambda} = 0. \end{aligned}$$

Hence, by the Lindeberg - Feller CLT and (f)

$$\underline{\lambda}^T \sqrt{n} (\underline{\hat{\beta}} - \underline{\beta}) \to_d N_p(0, \underline{\lambda}^T V^{-1} \underline{\lambda} \sigma^2).$$

By the Cramér - Wold device, this yields (e) under the hypothesis $\max h_{ii} \to 0$.
(d) To calculate the variance, we first note that from (a) $E(\hat{\epsilon}) = (I - H) E(\epsilon) = 0$, and $E(Z_n) = 0$. Similarly,

$$\begin{aligned} Var(Z_n) &= \frac{1}{n} (\underline{1}^T (I - H)(I - H) \underline{1}) \sigma^2 \\ &= \sigma^2 \left\{ 1 - (n^{-1} \underline{1}^T X)(n^{-1} X^T X)^{-1} (n^{-1} X^T \underline{1}) \right\}. \end{aligned}$$

(e) If $n^{-1} X^T \underline{1} \to h$, $n^{-1} X^T X \to V$ with V positive definite, and $h^T V^{-1} h < 1$, then from (d)

$$\begin{aligned} Var(Z_n) &= \sigma^2 \left\{ 1 - (n^{-1} \underline{1}^T X)(n^{-1} X^T X)^{-1} (n^{-1} X^T \underline{1}) \right\} \\ &\to \sigma^2 \{1 - h^T V^{-1} h\} \equiv \sigma^2 c^2 > 0. \end{aligned}$$

To show that $Z_n \to_d$ using the Lindeberg - Feller CLT requires a bit more in the way of hypotheses and some more work: write

$$Z_n = n^{-1/2} \underline{1}^T (I - H) \underline{\epsilon} \equiv \sum_{i=1}^n c_{ni} \epsilon_i \equiv \sum_{i=1}^n X_{ni};$$

thus the vector $\underline{c}_n = n^{-1/2}(I - H)\underline{1}$. Thus $E(X_{ni}) = 0$, $\sigma_{ni}^2 = Var(X_{ni}) = c_{ni}^2 \sigma^2$, and, as above,

$$\begin{aligned} \sigma_n^2 &= \sum_{i=1}^n \sigma_{ni}^2 = \sigma^2 \sum_{i=1}^n c_{ni}^2 = \sigma^2 \underline{c}^T \underline{c} \\ &= \sigma^2 \{1 - n^{-1} \underline{1}^T X (X^T X)^{-1} X^T \underline{1}\} \to \sigma^2 (1 - h^T V^{-1} h) \end{aligned}$$

under the above hypotheses. Finally, if $\max_{1 \le i \le n} |c_{ni}| \to 0$, then, for $\epsilon > 0$,

$$\begin{aligned} &\frac{1}{\sigma_n^2} \sum_{i=1}^n E\{|X_{ni}|^2 1_{[|X_{ni}| > \epsilon \sigma_n]}\} \\ &\quad = \frac{1}{\sigma_n^2} \sum_{i=1}^n c_{ni}^2 E\{\epsilon_1^2 1_{[|\epsilon_1| > \epsilon \sigma_n / |c_{ni}|]}\} \\ &\quad \le \frac{1}{\sigma^2} E\{\epsilon_1^2 1_{[|\epsilon_1| > \epsilon \sigma_n / \max_i |c_{ni}|]}\} \\ &\quad \to 0 \qquad \text{by the DCT since } \; E(\epsilon^2) < \infty \end{aligned}$$

if $\max_{1 \le i \le n} |c_{ni}|^2 \to 0$. But

$$\begin{aligned} |c_{ni}| &\le n^{-1/2} + n^{-1/2} \Big| \sum_{j=1}^n h_{ij} \Big| = n^{-1/2} + n^{-1/2} \underline{1}^T \underline{h} \\ &\le n^{-1/2} + n^{-1/2} \sqrt{\underline{1}^T \underline{1}} \sqrt{\underline{hh}} \\ &= n^{-1/2} + \sqrt{\sum_{j=1}^n h_{ij}^2} = n^{-1} + \sqrt{h_{ii}}, \end{aligned}$$

using $H = H^T$ and $HH = H$, so $\max_i |c_{ni}| \le n^{-1/2} + \sqrt{\max_i h_{ii}} \to 0$ by (iii). Thus the Lindeberg - Feller CLT yields $Z_n / \sigma_n \to_d N(0, 1)$; combining this with (d) yields

$$\sqrt{n} E_* (\hat{\beta}^* - \hat{\beta}) \to_d V^{-1} h N(0, c^2 \sigma^2).$$

We conclude from (e) and (i) that the bootstrap *fails* in the situation (at least under the additional hypothesis that $\max h_{ii} \to 0$).

4. Suppose now that the bootstrap residuals are drawn from the collection of *centered* residuals $\hat{\epsilon} - \mathbf{1}(\mathbf{1}^T\hat{\epsilon}/\mathbf{n})$ Compute $E_*(\sqrt{n}(\hat{\beta}^* - \hat{\beta}))$ and $E_*(\sqrt{n}(\hat{\beta}^* - \hat{\beta}))^{\otimes 2}$ for this bootstrap resampling scheme.

   Solution: When the resampling is done from the *centered* residuals $\underline{\hat{\epsilon}} - \underline{1}(\underline{1}^T\underline{\hat{\epsilon}}/n)$, the nonzero term in $E_*(\sqrt{n}(\underline{\hat{\beta}}^* - \underline{\hat{\beta}}))$ which we investigated in problem 4 above vanishes: Since

$$\sqrt{n}(\underline{\hat{\beta}}^* - \underline{\hat{\beta}}) = (X^TX)^{-1}X^T\underline{\hat{\epsilon}}^*,$$

   where

$$E_*(\underline{\hat{\epsilon}}^*) = \underline{1}\frac{1}{n}\sum_{i=1}^{n}(\hat{\epsilon}_i - \underline{1}^T\underline{\hat{\epsilon}}/n) = \underline{0},$$

   it follows that

$$E_*\{\sqrt{n}(\underline{\hat{\beta}}^* - \underline{\hat{\beta}}))\} = (X^TX)^{-1}X^TE_*(\underline{\hat{\epsilon}}^*) = \underline{0}.$$

   Furthermore,

$$\begin{aligned} E_*\{[\sqrt{n}(\underline{\hat{\beta}}^* - \underline{\hat{\beta}})]^{\otimes 2}\} &= n(X^TX)^{-1}X^TE_*(\underline{\hat{\epsilon}}^*\underline{\hat{\epsilon}}^{*T})X(X^TX)^{-1} \\ &= n(X^TX)^{-1}\hat{\sigma}_F^2 \end{aligned}$$

   since

$$E_*(\underline{\hat{\epsilon}}^*\underline{\hat{\epsilon}}^{*T}) = I\frac{1}{n}\sum_{i=1}^{n}(\hat{\epsilon}_i - \underline{1\hat{\epsilon}}/n)^2 \equiv \hat{\sigma}_F^2 I.$$

   This modification of the bootstrap procedure seems appropriate when the design matrix X does not contain a column of 1's. See Freedman (1981), *Ann. Statist.* **9**, 1218 - 1228; especially the discussion on page 1220, the positive theorem on page 1223, and the discussion on page 1224 (upon which this problem is based).