Estimation with Overidentifying Inequality Moment Conditions – Technical Appendix

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1 Consistency

For a precise definition of the notation see the main text.

1.1 Assumptions

Assumption 1 *(a)* X_i, $i = 1, \ldots, n$ *are strictly stationary on a probability space* $(\Omega_n, \mathcal{F}_n, P_n)$;
(b) Θ *is an* m*-dimensional compact subset of* $\mathbb{R}^m$*, where* $m \leq h_1$*,* $\theta_{n,0} \longrightarrow \theta_0$*,* $\theta_{n,0} \in \Theta$ $\forall$ n*, and* $\theta_0 \in \Theta$*;*
(c) $g(x, \theta)$ *is continuous at each* $\theta \in \Theta$ *with probability one;*
(d) $\mathbb{E}_n[g_1(X_i, \theta_{n,0})] = 0$*, and* $\inf_n \, \|\mathbb{E}_n[g_1(X_i, \theta)]\| > 0$ *for* $\theta \neq \theta_{n,0}$*;*
(e) $\nu_{n,0} \longrightarrow \nu_0$ *and* $\sqrt{n}\nu_{n,0} \longrightarrow u_0 \in [0, \infty]^{h_2}$*;*
(f) $\mathbb{E}_n[g(X_i, \theta_{n,0})g(X_i, \theta_{n,0})'] \longrightarrow J$ *is non-singular;*
(g) $Z_n = O_p(1)$*;*
(h) $\mathbb{V} = \left\{\nu \in \mathbb{R}^{h_2} : \nu \geq 0 \text{ and } \|v\| \leq K\right\}$*,* $\nu_{n,0} \in \mathbb{V}$ $\forall$ n*, and* ν_0 *lies in the interior of* $\mathbb{V}$*;*
(i) $\mathbb{E}_n\left[\sup_{\theta \in \Theta} \|g(X_i, \theta)\|^{\alpha}\right] \leq K < \infty$ *for some* $\alpha > 2$*;*
(j) for any θ *and* θ^**,* $\|g(X_i, \theta) - g(X_i, \theta^*)\| \leq L(X_i)\, l(\|\theta - \theta^*\|)$*, for some measurable function* L *of* X_i *such that* $\sup_n \mathbb{E}_n(L(X_i)) < \infty$*, and* $l(y) \downarrow 0$ *as* $y \downarrow 0$*.*

1.2 Main Results

Theorem 1 *Suppose that Assumption 1 is satisfied. Then* $\hat{\theta}_n - \theta_{n,0} \xrightarrow{p} 0$ *and* $\hat{\nu}_n - \nu_{n,0} \xrightarrow{p} 0$*. Moreover,* $\hat{\lambda}(\hat{\theta}_n, \hat{\nu}_n) \xrightarrow{p} 0$*.*

Throughout this appendix we are frequently using the following results. Notice that Assumption 1 implies that

$$\max_{1 \leq i \leq n} \sup_{\theta \in \Theta} \|g(X_i, \theta)\| = O_p\left(n^{1/\alpha}\right), \tag{1}$$

$$\frac{1}{n}\sum_{i=1}^{n} \sup_{\theta \in \Theta} \|g(X_i, \theta)\|^{\alpha} = O_p(1), \tag{2}$$

$$\sup_{\theta \in \Theta} \left\| \frac{1}{n}\sum_{i=1}^{n} \left\{ g(X_i, \theta)\, g(X_i, \theta)' - \mathbb{E}\left[g(X_i, \theta)\, g(X_i, \theta)'\right] \right\} \right\| = o_p(1). \tag{3}$$

According to Assumptions 1 and 1,

$$\mathbb{E}\left[g^{(1)}(X_i, \theta)\right] \text{ and } \mathbb{E}\left[g_j^{(2)}(X_i, \theta)\right] \tag{4}$$

are equicontinuous uniformly in θ, and

$$\sup_{\theta \in \Theta} \left\| \frac{1}{n}\sum_{i=1}^{n} \left\{ g^{(1)}(X_i, \theta) - \mathbb{E}\left[g^{(1)}(X_i, \theta)\right] \right\} \right\| = o_p(1) \tag{5}$$

$$\sup_{\theta \in \Theta} \left\| \frac{1}{n}\sum_{i=1}^{n} \left\{ g_j^{(2)}(X_i, \theta) - \mathbb{E}\left[g_j^{(2)}(X_i, \theta)\right] \right\} \right\| = o_p(1) \text{ for all } j = 1, ..., h.$$

(See, for instance, Andrews (1992)).

Proof of Theorem 1: We have to show that for any $\delta > 0$

$$\lim_{n \longrightarrow \infty} P\left\{\hat{\theta}_n \in \mathbb{B}(\theta_{n,0}, \delta), \hat{\nu}_n \in \mathbb{B}(\nu_{n,0}, \delta)\right\} = 1,$$

where

$$\mathbb{B}(\theta, \delta) = \{\tilde{\theta} \in \Theta \bigm| \|\theta - \tilde{\theta}\| < \delta\}, \quad \mathbb{B}(\nu, \delta) = \{\tilde{\nu} \in \mathbb{V} \bigm| \|\nu - \tilde{\nu}\| < \delta\}.$$

Define

$$\Theta_0^c = \Theta \cap \mathbb{B}\left(\theta_{n,0}, \delta\right)^c \quad \text{and} \quad N_0^c = \mathbb{V} \cap \mathbb{B}\left(\nu_{n,0}, \delta\right)^c.$$

To simplify the notation we omit the subscript n from the sets Θ_0^c and N_0^c. Recall that according to Assumption 1(i), the constant $\alpha > 2$ is such that $\mathbb{E}[\sup_{\theta \in \Theta} \|g(X_i, \theta)\|^\alpha] < K$. We show the following two statements are true: (i) For a given $\varepsilon, \delta > 0$ and ζ such that $\frac{1}{\alpha} < \zeta < \frac{1}{2}$, there exist positive constants η and κ and $\bar{n}$ such that for $n \geq \bar{n}$

$$P\left\{\bar{G}_n^*\left(\theta_{n,0}, \nu_{n,0}\right) \geq n^{-\zeta-\kappa}\eta\right\} < \frac{\varepsilon}{2}, \tag{6}$$

where

$$\bar{G}_n^*(\theta_{n,0}, \nu_{n,0}) = \max_{\lambda \in \hat{\Lambda}_n(\theta_{n,0})} G_n^*(\theta_{n,0}, \nu_{n,0}, \lambda),$$

and (ii)

$$P\left\{\min_{\theta \in \Theta_0^c,\ \nu \in N_0^c} \bar{G}_n^*\left(\theta, \nu\right) \leq n^{-\zeta}\eta\right\} < \frac{\varepsilon}{2}. \tag{7}$$

Then, from (6) and (7) we deduce that there exists an $\eta > 0$ such that for $n \geq \bar{n}$:

$$\begin{aligned} & P\left\{\hat{\theta}_n \in \mathbb{B}\left(\theta_{n,0}, \delta\right),\ \hat{\nu}_n \in \mathbb{B}(\nu_{n,0}, \delta)\right\} \\ \geq\ & P\left\{\bar{G}_n^*\left(\theta_{n,0}, \nu_{n,0}\right) < n^{-\zeta-\kappa}\eta,\ \min_{\theta \in \Theta_0^c,\ \nu \in N_0^c} \bar{G}_n^*\left(\theta, \nu\right) > n^{-\zeta}\eta\right\} \geq 1 - \epsilon. \end{aligned}$$

Proof of (i): By Lemma 2 $\bar{G}_n^*(\theta_{n,0}, \nu_{n,0}) \leq O_p(1/n)$. Choose $\kappa > 0$ such that $\zeta + \kappa < 1$. Then

$$n^{\zeta+\kappa}\bar{G}_n^*(\theta_{n,0}, \nu_{n,0}) \leq O_p(n^{\zeta+\kappa-1}) = o_p(1)$$

as required.

Proof of (ii): To obtain a lower bound for $\bar{G}_n^*(\theta, \nu)$ we will evaluate the function $G_n^*(\theta, \nu, \lambda)$ at $\lambda = n^{-\zeta}u(\theta, \nu)$, where the function $u(\theta, \nu)$ is defined as

$$u(\theta, \nu) = \begin{cases} 0 & \text{if } \theta = \theta_{n,0},\ \nu = \nu_{n,0} \\ \frac{\boldsymbol{E}[g(X_i,\theta)] - M'\nu}{\|\boldsymbol{E}[g(X_i,\theta)] - M'\nu\|} & \text{otherwise} \end{cases}$$

such that $\|u(\theta, \nu)\| \leq 1$.

Moreover, we truncate the function $g(x, \theta)$ as follows. Since $\alpha > 2$, we can choose a positive constant ξ such that

$$\frac{1}{\alpha^2} < \xi < \frac{1}{2\alpha}.$$

Let

$$\mathcal{X}_n = \left\{ x : \sup_{\theta \in \Theta} \| g(x, \theta) \| \leq n^{\xi} \right\} \quad \text{and} \quad g_n(x, \theta) = I\{x \in \mathcal{X}_n\} g(x, \theta).$$

We then replace the terms

$$\ln(1 + \lambda' g(x, \theta)) - \lambda' M' \nu$$

in the definition of the objective function $G_n^*(\theta, \nu, \lambda)$ by

$$q_n(x, \theta, \nu) = \ln\left(1 + n^{-\zeta} u'(\theta, \nu) g_n(x, \theta)\right) - n^{-\zeta} u'(\theta, \nu) M' \nu.$$

In what follows, we deduce the required result for (ii) by showing that

$$\text{(ii)-(a):} \quad \min_{\theta \in \Theta_0^c, \nu \in N_0^c} \frac{1}{n} \sum_{i=1}^n q_n(X_i, \theta, \nu) \leq \min_{\theta \in \Theta_0^c, \nu \in N_0^c} \bar{G}_n^*(\theta, v) + o_p\left(n^{-\zeta}\right)$$

and

$$\text{(ii)-(b):} \quad P\left\{ \min_{\theta \in \Theta_0^c, \nu \in N_0^c} \frac{1}{n} \sum_{i=1}^n q_n(X_i, \theta, \nu) < n^{-\zeta} \eta \right\} \leq \frac{\varepsilon}{2}.$$

Proof of (ii)-(a): Notice that $n^{-\zeta} u(\theta, \nu) \in \Lambda_n^{\zeta} \subset \cap_{\theta \in \Theta} \hat{\Lambda}_n(\theta)$ w.p.a.1 by Lemma 1. Then, by Lemma 4 and by the definition of $\hat{\lambda}_n(\theta, v)$,

$$\begin{aligned}
&\min_{\theta \in \Theta_0^c, \nu \in N_0^c} \frac{1}{n} \sum_{i=1}^n q_n(X_i, \theta, \nu) \\
&= \min_{\theta \in \Theta_0^c, \nu \in N_0^c} \left[\frac{1}{n} \sum_{i=1}^n \ln\left(1 + n^{-\zeta} u'(\theta, \nu) g(X_i, \theta)\right) - n^{-\zeta} u'(\theta, \nu) M' \nu \right] + o_p\left(n^{-\zeta}\right) \\
&\leq \min_{\theta \in \Theta_0^c, \nu \in N_0^c} \left[\frac{1}{n} \sum_{i=1}^n \ln\left(1 + \hat{\lambda}_n'(\theta, v) g(X_i, \theta)\right) - \hat{\lambda}_n'(\theta, v) M' \nu \right] + o_p\left(n^{-\zeta}\right) \\
&= \min_{\theta \in \Theta_0^c, \nu \in N_0^c} \bar{G}_n^*(\theta, v) + o_p\left(n^{-\zeta}\right),
\end{aligned}$$

as required.

Proof of (ii)-(b): A second-order Taylor expansion of q_n around $u(\theta, \nu) = 0$ yields

$$n^{\zeta} q_n(x, \theta, \nu) = u(\theta, \nu)'(g_n(x, \theta) - M'\nu) - \frac{1}{2} \frac{n^{-\zeta} u'(\theta, \nu) g_n(x, \theta) g_n(x, \theta)' u(\theta, \nu)}{\left(1 + n^{-\zeta} u_*'(\theta, \nu) g_n(x, \theta)\right)^2}, \tag{8}$$

where $u_*(\theta, \nu)$ lies between zero and $u(\theta, \nu)$. The second-order term of the Taylor approximation (8) can be bounded as follows. For given x, θ, and ν

$$\sup_{\theta \in \Theta, \, \nu} \left| n^{-\zeta} u_*'(\theta, \nu) g_n(x, \theta) \right| \leq n^{-\zeta} \sup_{\theta \in \Theta} \| g_n(x, \theta) \| \leq n^{-\zeta + \xi} \leq n^{-\zeta/2}$$

since $\xi < \frac{1}{2\alpha} < \frac{\zeta}{2}$. Therefore,

$$\sup_{\theta \in \Theta, \, \nu} n^{-\zeta} \frac{u(\theta, \nu)' g_n(x, \theta) g_n(x, \theta)' u(\theta, \nu)}{\left(1 + n^{-\zeta} u_*(\theta, \nu)' g_n(x, \theta)\right)^2} \leq \sup_{\theta \in \Theta, \, \nu} n^{-\zeta} \frac{\| g_n(x, \theta) \|^2 \| u(\theta, \nu) \|^2}{(1 - n^{-\zeta/2})^2} \leq n^{-\zeta + 2\xi} = o(1). \tag{9}$$

Now consider the expected value of $n^{\zeta}q_n(x,\theta,\nu)$. From (8), (9), and by the dominated convergence theorem, we have

$$\begin{aligned} n^{\zeta}\mathbb{E}\left[q_n\left(X_i,\theta,\nu\right)\right] &= u'(\theta,\nu)(\mathbb{E}[g_n(X_i,\theta)]-M'\nu)+o(1) \\ &= \begin{cases} o(1) & \text{if } \theta=\theta_0,\ \nu=\nu_{n,0} \\ \|\mathbb{E}[g(X_i,\theta)]-M'\nu\|+o(1)>0 & \text{otherwise} \end{cases}. \end{aligned} \tag{10}$$

The $o(1)$ terms absorb the second-order term of the Taylor approximation and the discrepancy between $\mathbb{E}[g_n(X,\theta)]$ and $\mathbb{E}[g(X,\theta)]$, which vanishes as $\mathcal{X}_n$ expands. From (10) and the monotone convergence theorem we can deduce that

$$\lim_{n\to\infty} n^{\zeta}\lim_{\delta\downarrow 0}\mathbb{E}\left[\inf_{\theta^*\in\mathbb{B}(\theta,\delta),\ \nu^*\in\mathbb{B}(\nu,\delta)} q_n\left(X_i,\theta^*,\nu^*\right)\right] \begin{cases} =0 & \text{if } \theta=\theta_{n,0},\ \nu=\nu_{n0} \\ >0 & \text{otherwise} \end{cases}.$$

Since Θ and $\mathbb{V}$ are compact by assumption, the sets $\Theta\cap\mathbb{B}(\theta_{n,0},\delta)^c$ and $\mathbb{V}\cap\mathbb{B}(\nu_{n,0},\delta)^c$ are compact. We can cover both $\Theta\cap\mathbb{B}(\theta_{n,0},\delta)^c$ and $\mathbb{V}\cap\mathbb{B}(\nu_{n,0},\delta)^c$ with $\Theta_j=\mathbb{B}(\theta_j,\delta_j)$ and $N_j=\mathbb{B}(\nu_j,\delta_j)$'s, $j=1,\ldots,J$ taking each δ_j small enough such there exist η_j's such that

$$n^{\zeta}\mathbb{E}\left[\inf_{\theta\in\Theta_j,\ \nu\in N_j} q_n\left(X_i,\theta,\nu\right)\right]\geq 2\eta_j,\ n\geq n_j \tag{11}$$

for some positive numbers $\eta_j=\eta_j\left(\delta\right)$, $j=1,\ldots,J$. By the WLLN[1] and (11), for a given $\varepsilon>0$, we can find $\bar{n}_j's$ such that $n\geq\bar{n}_j$ implies that

$$\begin{aligned} \frac{\varepsilon}{2J} &\geq P\left\{\left|\frac{1}{n}\sum_{i=1}^{n} n^{\zeta}\inf_{\theta\in\Theta_j,\ \nu\in N_j} q_n\left(X_i,\theta,\nu\right)-\mathbb{E}\left[n^{\zeta}\inf_{\theta\in\Theta_j,\ \nu\in N_j} q_n\left(X_i,\theta,\nu\right)\right]\right|>\eta_j\right\} \\ &\geq P\left\{\frac{1}{n}\sum_{i=1}^{n}\inf_{\theta\in\Theta_j,\ \nu\in N_j} q_n\left(X_i,\theta,\nu\right)<\mathbb{E}\left[\inf_{\theta\in\Theta_j,\ \nu\in N_j} q_n\left(X_i,\theta,\nu\right)\right]-n^{-\zeta}\eta_j\right\} \\ &\geq P\left\{\frac{1}{n}\sum_{i=1}^{n}\inf_{\theta\in\Theta_j,\ \nu\in N_j} q_n\left(X_i,\theta,\nu\right)<n^{-\zeta}\eta_j\right\} \\ &\geq P\left\{\inf_{\theta\in\Theta_j,\ \nu\in N_j}\frac{1}{n}\sum_{i=1}^{n} q_n\left(X_i,\theta,\nu\right)<n^{-\zeta}\eta_j\right\} \end{aligned}$$

for $j=1,\ldots,J$. Now let letting $\eta=\min\left\{\eta_1,\ldots,\eta_J\right\}$ and $\bar{n}=\max_{j=1,\ldots,J}\ \bar{n}_j$, we have for $n\geq\bar{n}$

$$\begin{aligned} & P\left\{\min_{\theta\in\Theta_0^c,\ \nu\in N_0^c}\frac{1}{n}\sum_{i=1}^{n} q_n\left(X_i,\theta,\nu\right)<n^{-\zeta}\eta\right\} \\ &\quad\leq P\left\{\min_{j=1,\ldots,J}\left\{\inf_{\theta\in\Theta_j,\ \nu\in N_j}\frac{1}{n}\sum_{i=1}^{n} q_n(X_i,\theta,\nu)\right\}<n^{-\zeta}\eta\right\} \\ &\quad\leq \sum_{j=1}^{J} P\left\{\inf_{\theta\in\Theta_j,\ \nu\in N_j}\frac{1}{n}\sum_{i=1}^{n} q_n(X_i,\theta,\nu)<n^{-\zeta}\eta_j\right\}\leq\frac{\varepsilon}{2}, \end{aligned}$$

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[1] Notice that

$$\mathbb{E}\left[\left(n^{\zeta}\inf_{\theta\in\Theta_j,\ \nu\in N_j} q_n\left(X_i,\theta,\nu\right)\right)^2\right]\leq\mathbb{E}\left[\sup_{\theta\in\Theta} 2\left\|g\left(X_i,\theta\right)\right\|^2\right]+2K+n^{-2\zeta+4\xi}<\infty. \tag{12}$$

as required part (ii)-(b).

Combining (ii)-(a) and (ii)-(b) we have

$$P\left\{\min_{\theta\in\Theta_0^c,\nu\in N_0^c}\bar{G}_n^*\left(\theta,\nu\right)<n^{-\zeta}\eta\right\}\leq\frac{\varepsilon}{2},$$

as required for (ii).

Since $\hat{\theta}_n - \theta_{n,0} \overset{p}{\longrightarrow}$ and $\hat{\nu}_n - \nu_{n,0} \overset{p}{\longrightarrow} 0$ we can deduce from Lemmas 2 and 3 that $\hat{\lambda}(\hat{\theta}_n, \hat{\nu}_n) \overset{p}{\longrightarrow} 0$. ■

1.3 Technical Lemmas

Lemma 1 *Suppose that Assumption 1 is satisfied. Then,*

(i) $\sup_{\theta\in\Theta,\lambda\in\Lambda_n^\zeta,1\leq i\leq n}\left|\lambda' g\left(X_i,\theta\right)\right| \longrightarrow_p 0,$

(ii) $\Lambda_n^\zeta \subseteq \bigcap_{\theta\in\Theta}\hat{\Lambda}_n(\theta)$ *w.p.a. 1.*

Proof of Lemma 1: See proof of Lemma A1 in Newey and Smith (2004). ■

Lemma 2 *Suppose that Assumption 1 is satisfied. Let $\bar{\theta}\in\Theta$ and $\bar{\nu}\geq 0$ be sequences such that $\bar{\theta}-\theta_{n,0}\overset{p}{\longrightarrow}0$, and $\bar{\nu}-\nu_{n,0}\overset{p}{\longrightarrow}0$. Moreover, $\frac{1}{\sqrt{n}}\sum_{i=1}^n g_1(X_i,\bar{\theta})=O_p(1)$ and $\frac{1}{\sqrt{n}}\sum_{i=1}^n\left(g_2(X_i,\bar{\theta})-\bar{\nu}\right)=O_p(1)$. Then,*

(i) $\hat{\lambda}(\bar{\theta},\bar{\nu})$ *exists w.p.a. 1,*

(ii) $\hat{\lambda}(\bar{\theta},\bar{\nu})=O_p(n^{-1/2})$,

(iii) $G_n^*\left(\bar{\theta},\bar{\nu},\hat{\lambda}(\bar{\theta},\bar{\nu})\right)\leq O_p\left(\frac{1}{n}\right).$

Proof of Lemma 2: The proof is similar to that of Lemma A2 in Newey and Smith (2004).

Proof of (i): Define

$$\tilde{\lambda}(\bar{\theta},\bar{\nu})=\arg\max_{\lambda\in\Lambda_n^\zeta}G_n^*(\bar{\theta},\bar{\nu},\lambda)$$

Since Λ_n^ζ is compact and $\ln\left(1+\lambda' g(X_i,\bar{\theta})\right)-\bar{\nu}' M\lambda$ is continuous and strictly concave in λ the optimal solution $\tilde{\lambda}(\bar{\theta},\bar{\nu})$ exists and is unique. Statement (i) then follows from Lemma 1.

Proof of (ii) and (iii): Write $\bar{g}_i = g(X_i, \bar{\theta})$. For some constant C

$$
\begin{aligned}
0 = G_n^*(\bar{\theta}, \bar{\nu}, 0) &\leq G_n^*(\bar{\theta}, \bar{\nu}, \tilde{\lambda}(\bar{\theta}, \bar{\nu})) \\
&= \frac{1}{n}\sum_{i=1}^{n} \ln\left(1 + \tilde{\lambda}'(\bar{\theta}, \bar{\nu})\bar{g}_i\right) - \bar{\nu}' M \tilde{\lambda}(\bar{\theta}, \bar{\nu}) \\
&= \tilde{\lambda}'(\bar{\theta}, \bar{\nu})\left(\frac{1}{n}\sum_{i=1}^{n} \bar{g}_i - M'\bar{\nu}\right) - \frac{1}{2}\tilde{\lambda}'(\bar{\theta}, \bar{\nu})\left(\frac{1}{n}\sum_{i=1}^{n} \frac{\bar{g}_i\bar{g}_i'}{(1 + \lambda_*'\bar{g}_i)^2}\right)\tilde{\lambda}(\bar{\theta}, \bar{\nu}) \\
&\leq \tilde{\lambda}'(\bar{\theta}, \bar{\nu})\left(\frac{1}{n}\sum_{i=1}^{n} \bar{g}_i - M'\bar{\nu}\right) - \frac{C}{4}\tilde{\lambda}'(\bar{\theta}, \bar{\nu})\tilde{\lambda}(\bar{\theta}, \bar{\nu}),
\end{aligned}
$$

where λ_* lies on the line joining $\tilde{\lambda}(\bar{\theta}, \bar{\nu})$ and 0. The last inequality holds because

$$\max_{1 \leq i \leq n} |\lambda_*'\bar{g}_i| = o_p(1)$$

according to Lemma 1 and $\frac{1}{n}\sum_{i=1}^{n} \bar{g}_i\bar{g}_i'$ converges in probability to J, a positive definite matrix, by (3) and Assumption 1(f). The remainder of the proof follows the proof of Lemma A2 in Newey and Smith (2004). ■

Lemma 3 *Suppose Assumption 1 is satisfied. Then,*

$$\frac{1}{\sqrt{n}}\sum_{i=1}^{n}\left[g\left(X_i, \hat{\theta}\right) - M'\hat{v}\right] = O_p(1).$$

Proof of Lemma 3: The proof is similar to that of Lemma A.3 in Newey and Smith (2004).

Let $\hat{g}_i = g\left(X_i, \hat{\theta}\right) - M'\hat{\nu}$ and $\hat{g} = \frac{1}{n}\sum_{i=1}^{n}\left[g\left(X_i, \hat{\theta}\right) - M'\hat{\nu}\right]$. Define $\hat{u}\left(\hat{\theta}, \hat{\nu}\right) = n^{-\zeta}\frac{\hat{g}}{\|\hat{g}\|}$. (Recall the definition of $u(\theta, \nu)$ in the proof of consistency.) Approximation $G_n^*(\theta, \nu, \lambda)$ with respect to λ around $\lambda = 0$ at $(\theta, \nu, \lambda) = \left(\hat{\theta}, \hat{\nu}, \hat{u}\left(\hat{\theta}, \hat{\nu}\right)\right)$. Then,

$$
\begin{aligned}
&G_n^*\left(\hat{\theta}, \hat{\nu}, \hat{u}\left(\hat{\theta}, \hat{\nu}\right)\right) \\
&= G_n^*\left(\hat{\theta}, \hat{\nu}, 0\right) + \frac{\partial G_n^*\left(\hat{\theta}, \hat{\nu}, 0\right)}{\partial \lambda'}\hat{u}\left(\hat{\theta}, \hat{\nu}\right) + \frac{1}{2}\hat{u}'\left(\hat{\theta}, \hat{\nu}\right)\frac{\partial^2 G_n^*\left(\hat{\theta}, \hat{\nu}, \ddot{\lambda}\right)}{\partial\lambda\partial\lambda'}\hat{u}\left(\hat{\theta}, \hat{\nu}\right) \\
&= \hat{g}'\hat{u}\left(\hat{\theta}, \hat{\nu}\right) - \frac{1}{2}\hat{u}'\left(\hat{\theta}, \hat{\nu}\right)\left(\frac{1}{n}\sum_{i=1}^{n}\frac{\hat{g}_i\hat{g}_i'}{\left(1 + \ddot{\lambda}'\hat{g}_i\right)^2}\right)\hat{u}\left(\hat{\theta}, \hat{\nu}\right),
\end{aligned}
$$

where $\ddot{\lambda}$ is located between 0 and $\hat{u}(\hat{\theta}, \hat{\nu})$.

Notice that $\max_{1 \leq i \leq n}\left|\hat{u}'(\hat{\theta}, \hat{\nu})\hat{g}_i\right| \to_p 0$ and $\hat{u}\left(\hat{\theta}, \hat{\nu}\right) \in \hat{\Lambda}_n\left(\hat{\theta}\right)$ by Lemma A.1 w.p.a.1. Also, under Assumption 1 $\left\|\frac{1}{n}\sum_{i=1}^{n}\hat{g}_i\hat{g}_i'\right\| \leq 2\left(\frac{1}{n}\sum_{i=1}^{n}\sup_{\theta\in\Theta}\|g(X_i, \theta)\|^2 + K\right) = O_p(1)$.

Then, w.p.a.1, for some constant C,

$$\begin{aligned}
&\hat{g}'\hat{u}\left(\hat{\theta},\hat{\nu}\right)-\frac{1}{2}\hat{u}'\left(\hat{\theta},\hat{\nu}\right)\left(\frac{1}{n}\sum_{i=1}^{n}\frac{\hat{g}_i\hat{g}_i'}{\left(1+\ddot{\lambda}'\hat{g}_i\right)^2}\right)\hat{u}\left(\hat{\theta},\hat{\nu}\right)\\
&= n^{-\zeta}\|\hat{g}\|-\frac{1}{2}\hat{u}'\left(\hat{\theta},\hat{\nu}\right)\left(\frac{1}{n}\sum_{i=1}^{n}\frac{\hat{g}_i\hat{g}_i'}{\left(1+\ddot{\lambda}'\hat{g}_i\right)^2}\right)\hat{u}\left(\hat{\theta},\hat{\nu}\right)\\
&\geq n^{-\zeta}\|\hat{g}\|-\frac{1}{2}\max_{1\leq i\leq n}\left(\frac{1}{\left(1+\ddot{\lambda}'\hat{g}_i\right)^2}\right)\hat{u}'\left(\hat{\theta},\hat{\nu}\right)\left(\frac{1}{n}\sum_{i=1}^{n}\hat{g}_i\hat{g}_i'\right)\hat{u}\left(\hat{\theta},\hat{\nu}\right)\\
&\geq n^{-\zeta}\|\hat{g}\|-Cn^{-2\zeta}. \qquad (13)
\end{aligned}$$

Then,

$$n^{-\zeta}\|\hat{g}\|-Cn^{-2\zeta}\leq G_n^*\left(\hat{\theta},\hat{\nu},\hat{u}\left(\hat{\theta},\hat{\nu}\right)\right)\leq G_n^*\left(\hat{\theta},\hat{\nu},\hat{\lambda}\right)\leq\sup_{\lambda\in\hat{\Lambda}_n(\theta_{n,0})}G_n^*\left(\theta_{n,0},\nu_{n,0},\lambda\right)\leq O_p\left(\frac{1}{n}\right), \qquad (14)$$

where the first inequality is from (13), the second and third inequalities hold because $\left(\hat{\theta},\hat{\nu},\hat{\lambda}\right)$ is a saddle point, and the last inequality is from Lemma A.2 with

$$\frac{1}{\sqrt{n}}\sum_{i=1}^{n}\left[g\left(X_i,\theta_{n,0}\right)-M'\nu_{n,0}\right]=O_p\left(1\right)$$

by Assumption 1(g). Also, by $\zeta<\frac{1}{2}$, $\zeta-1<-\frac{1}{2}<-\zeta$. Solving (14) for $\|\hat{g}\|$ gives

$$\|\hat{g}\|\leq O_p\left(n^{-\zeta}\right). \qquad (15)$$

For a given sequence $\varepsilon_n\longrightarrow 0$, let $\bar{\lambda}=\varepsilon_n\hat{g}$. According to (15) $\bar{\lambda}=o_p\left(n^{-\zeta}\right)$. Hence, $\bar{\lambda}\in\Lambda_n^{\zeta}$ w.p.a.1. Then, as in (14), we have

$$\bar{\lambda}'\hat{g}-C\left\|\bar{\lambda}\right\|^2=\varepsilon_n\|\hat{g}\|^2-C\varepsilon_n^2\|\hat{g}\|^2\leq\varepsilon_n\|\hat{g}\|^2\left(1-C\varepsilon_n\right)\leq O_p\left(\frac{1}{n}\right).$$

For large enough n the term $1-C\varepsilon_n$ is bounded away from zero and it follows that $\varepsilon_n\|\hat{g}\|^2=O_p\left(\frac{1}{n}\right)$. Since ε_n is an arbitrary sequence that tends to zero, we deduce that

$$\|\hat{g}\|=O_p\left(\frac{1}{\sqrt{n}}\right),$$

as required. ■

Lemma 4 *Suppose that Assumption 1 is satisfied. Let* $g_n(x,\theta)=I\{x\in\mathcal{X}_n\}g(x,\theta)$ *where*

$$\mathcal{X}_n=\left\{x:\sup_{\theta\in\Theta}\|g\left(x,\theta\right)\|\leq n^{\xi}\right\},$$

where $\frac{1}{\alpha^2} < \xi < \frac{1}{2\alpha}$ *and* $\alpha > 2$ *as in Assumption 1(i). Define*

$$\begin{aligned} q_n\left(X_i,\theta,\nu\right) &= \ln\left[1+n^{-\zeta}u'(\theta,\nu)g_n(X_i,\theta)\right] - n^{-\zeta}u'(\theta,\nu)M'\nu \\ \tilde{q}_n\left(X_i,\theta,\nu\right) &= \ln\left[1+n^{-\zeta}u'(\theta,\nu)g(X_i,\theta)\right] - n^{-\zeta}u'(\theta,\nu)M'\nu \end{aligned}$$

and assume that $\|u(\theta,\nu)\| \leq 1$*. Then,*

$$\sup_{\theta\in\Theta,\ \nu\geq 0}\left|\frac{1}{n}\sum_{i=1}^{n}\left(q_n\left(X_i,\theta,\nu\right)-\tilde{q}_n\left(X_i,\theta,\nu\right)\right)\right| = o_p\left(n^{-\zeta}\right).$$

Proof of Lemma 4: By the mean value theorem,

$$\begin{aligned} &\sup_{\theta\in\Theta,\ \nu\geq 0}\left|\frac{1}{n}\sum_{i=1}^{n}\left\{q_n\left(X_i,\theta,\nu\right)-\tilde{q}_n\left(X_i,\theta,\nu\right)\right\}\right| \\ &= \sup_{\theta\in\Theta,\ \nu\geq 0}\left|\frac{1}{n}\sum_{i=1}^{n}\left(\frac{n^{-\zeta}u'(\theta,\nu)g\left(X_i,\theta\right)}{1+n^{-\zeta}u_*'\left(\theta,\nu\right)g\left(X_i,\theta\right)}\right)I\left\{X_i\notin\mathcal{X}_n\right\}\right| \qquad (16) \\ &\leq \max_{1\leq i\leq n}\sup_{\theta\in\Theta,\ \nu\geq 0}\left|\frac{n^{-\zeta}u'\left(\theta,\nu\right)g\left(X_i,\theta\right)}{1+n^{-\zeta}u_*'\left(\theta,\nu\right)g\left(X_i,\theta\right)}\right|\frac{1}{n}\sum_{i=1}^{n}I\left\{\sup_{\theta\in\Theta}\left\|g\left(X_i,\theta\right)\right\|>n^{\xi}\right\} \\ &\leq \frac{1}{n^{\alpha\xi}}\left(\max_{1\leq i\leq n}\sup_{\theta\in\Theta,\ \nu\geq 0}\left|\frac{n^{-\zeta}u'\left(\theta,\nu\right)g\left(X_i,\theta\right)}{1+n^{-\zeta}u_*'\left(\theta,\nu\right)g\left(X_i,\theta\right)}\right|\right)\left(\frac{1}{n}\sum_{i=1}^{n}\sup_{\theta\in\Theta}\left\|g\left(X_i,\theta\right)\right\|^{\alpha}\right) \end{aligned}$$

where $u_*(\theta,\nu)$ is located between 0 and $u(\theta,\nu)$. The second term on the right-hand side of (16) can be bounded as follows. According to (1)

$$n^{-\zeta}\max_{1\leq i\leq n}\sup_{\theta\in\Theta}\left\|g\left(X_i,\theta\right)\right\| = n^{-\zeta+1/\alpha}O_p\left(1\right).$$

Moreover, $\|u(\theta,\nu)\| \leq 1$. Therefore,

$$\begin{aligned} \max_{1\leq i\leq n}\sup_{\theta\in\Theta,\ \nu\geq 0}\left|\frac{n^{-\zeta}u'\left(\theta,\nu\right)g\left(X_i,\theta\right)}{1+n^{-\zeta}u_*'\left(\theta,\nu\right)g\left(X_i,\theta\right)}\right| &\leq \frac{2n^{-\zeta}\max_{1\leq i\leq n}\sup_{\theta\in\Theta}\left\|g\left(X_i,\theta\right)\right\|}{1-2n^{-\zeta}\max_{1\leq i\leq n}\sup_{\theta\in\Theta}\left\|g\left(X_i,\theta\right)\right\|} \\ &= \frac{n^{-\zeta+1/\alpha}O_p\left(1\right)}{1-n^{-\zeta+1/\alpha}O_p\left(1\right)} = n^{-\zeta+1/\alpha}O_p\left(1\right). \end{aligned}$$

By Assumption 1(i) and the Markov inequality, the third term on the right-hand side of (16) is $O_p(1)$. Since $\frac{1}{\alpha^2} < \xi < \frac{1}{2\alpha}$, we are able to deduce that

$$n^{\zeta}\sup_{\theta\in\Theta,\ \nu\geq 0}\left|\frac{1}{n}\sum_{i=1}^{n}\left(q_n\left(X_i,\theta,\nu\right)-\tilde{q}_n\left(X_i,\theta,\nu\right)\right)\right| = n^{-\alpha\xi+\frac{1}{\alpha}}O_p\left(1\right) = o_p\left(1\right),$$

as required. ■

2 Limit Distributions

Let $\beta = [\theta',\nu',\lambda']'$, $\beta_{n,0} = [\theta_{n,0}',\nu_{n,0}',0_{1\times h}]'$, and abbreviate $G_n^*(\theta,\nu,\lambda)$ as $G_n^*(\beta)$. The objective function is expanded around $\beta_{n,0}$ as follows:

$$G_n^*(\beta) = G_{nq}^*(\beta) + \frac{1}{n}\mathcal{R}_n(\beta), \qquad (17)$$

where

$$G_{nq}^*(\beta) = G_n^*(\beta_{n,0}) + G_n^{*(1)}(\beta_{n,0})(\beta - \beta_{n,0}) + \frac{1}{2}(\beta - \beta_{n,0})' G_n^{*(2)}(\beta_{n,0})(\beta - \beta_{n,0}).$$

We begin by deriving the coefficient matrices for the quadratic approximation of the objective function

$$G_{nq}^*\left(\beta\right) = G_n^*\left(\beta_{n,0}\right) + G_n^{*(1)}\left(\beta_{n,0}\right)'\left(\beta - \beta_{n,0}\right) + \frac{1}{2}\left(\beta - \beta_{n,0}\right)' G_n^{*(2)}\left(\beta_{n,0}\right)\left(\beta - \beta_{n,0}\right). \quad (18)$$

A direct calculation shows that

$$G_n^{*(1)}\left(\beta\right) = \left[G_n^{*(1)}\left(\beta\right)_\theta', G_n^{*(1)}\left(\beta\right)_\nu', G_n^{*(1)}\left(\beta\right)_\lambda'\right]', \quad (19)$$

where

$$\begin{aligned}
G_n^{*(1)}\left(\beta\right)_\theta &= \frac{1}{n}\sum_{i=1}^{n}\left(\frac{g^{(1)}\left(X_i,\theta\right)\lambda}{1+\lambda' g(X_i,\theta)}\right), \\
G_n^{*(1)}\left(\beta\right)_\nu &= -M\lambda, \\
G_n^{*(1)}\left(\beta\right)_\lambda &= \frac{1}{n}\sum_{i=1}^{n}\left(\frac{g(X_i,\theta)}{1+\lambda' g(X_i,\theta)}\right) - M'v.
\end{aligned}$$

At $\beta_{n,0}$ the first derivatives simplify to

$$G_n^{*(1)}(\beta_{n,0}) = [0, 0, n^{-1/2}Z_n']. \quad (20)$$

We proceed by partitioning the matrix of second derivative as follows

$$G_n^{*(2)}\left(\beta\right) = \begin{pmatrix} G_n^{*(2)}\left(\beta\right)_{\theta\theta'} & G_n^{*(2)}\left(\beta\right)_{\theta\nu'} & G_n^{*(2)}\left(\beta\right)_{\theta\lambda'} \\ G_n^{*(2)}\left(\beta\right)_{\nu\theta'} & G_n^{*(2)}\left(\beta\right)_{\nu\nu'} & G_n^{*(2)}\left(\beta\right)_{\nu\lambda'} \\ G_n^{*(2)}\left(\beta\right)_{\lambda\theta'} & G_n^{*(2)}\left(\beta\right)_{\lambda\nu'} & G_n^{*(2)}\left(\beta\right)_{\lambda\lambda'} \end{pmatrix}, \quad (21)$$

where

$$\begin{aligned}
G_n^{*(2)}(\beta)_{\theta\theta'} &= \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\sum_{j=1}^{h}\lambda_j g_j^{(2)}(X_i,\theta)}{1+\lambda' g(X_i,\theta)} - \frac{g^{(1)}\left(X_i,\theta\right)\lambda\lambda' g^{(1)}\left(X_i,\theta\right)'}{(1+\lambda' g(X_i,\theta))^2}\right), \\
G_n^{*(2)}\left(\beta\right)_{\theta\nu'} &= 0, \quad G_n^{*(2)}\left(\beta\right)_{\nu\nu'} = 0, \quad G_n^{*(2)}\left(\beta\right)_{\lambda\nu'} = -M', \\
G_n^{*(2)}\left(\beta\right)_{\lambda\theta'} &= \frac{1}{n}\sum_{i=1}^{n}\left(\frac{g^{(1)}\left(X_i,\theta\right)'}{1+\lambda' g(X_i,\theta)} - \frac{g\left(X_i,\theta\right)\lambda' g^{(1)}(X_i,\theta)'}{(1+\lambda' g(X_i,\theta))^2}\right), \\
G_n^{*(2)}\left(\beta\right)_{\lambda\lambda'} &= -\frac{1}{n}\sum_{i=1}^{n}\frac{g(X_i,\theta)g(X_i,\theta)'}{(1+\lambda' g(X_i,\theta))^2}.
\end{aligned}$$

At $\beta_{n,0}$ the second derivatives simplify to

$$G_n^{*(2)}(\beta_{n,0}) = \begin{bmatrix} 0 & 0 & Q_n \\ 0 & 0 & -M \\ Q_n' & -M' & -J_n \end{bmatrix}. \quad (22)$$

The objective function $G^*_{nq}(\beta)$ in terms of the transformed parameters is:

$$\begin{aligned}\mathcal{G}^*_{nq}(\phi,l) &= -\frac{1}{2}(l-J_n^{-1}[Z_n-R_n'(\phi-\phi_{n,0})])'J_n(l-J_n^{-1}[Z_n-R_n'(\phi-\phi_{n,0})]) \\ &\quad +\frac{1}{2}(Z_n-R_n'(\phi-\phi_{n,0}))'J_n^{-1}(Z_n-R_n'(\phi-\phi_{n,0}))\end{aligned} \quad (23)$$

The function $\mathcal{G}^*_{nq}(\phi,l)$ is maximized with respect to $l\in\mathbb{R}^h$ by

$$\tilde{l}_q(\phi) = J_n^{-1}(Z_n - R_n'(\phi-\phi_{n,0})) \quad (24)$$

and the concentrated objective function is:

$$\bar{\mathcal{G}}^*_{nq}(\phi) = \mathcal{G}^*_{nq}(\phi,\tilde{l}_q(\phi)) = \frac{1}{2}(Z_n-R_n'(\phi-\phi_{n,0}))'J_n^{-1}(Z_n-R_n'(\phi-\phi_{n,0})). \quad (25)$$

2.1 Assumptions

Assumption 2 *(a) The true parameter θ_0 exists in an interior of* Θ;
(b) $g(X_i,\theta)$ is twice continuously differentiable with respect to θ;
(c) the minimum eigenvalue of $(\mathbb{E}_n[g_1^{(1)}(X_i,\theta)])(\mathbb{E}_n[g_1^{(1)}(X_i,\theta)])'$ is bounded below by a constant $K>0$;
(d) $\mathbb{E}_n\left[\sup_{\theta\in\Theta}\|g^{(1)}(X_i,\theta)\|^2\right]\le K<\infty$, $\mathbb{E}_n[\sup_{\theta\in\Theta}\|g_j^{(2)}(X_i,\theta)\|]\le K<\infty$ for $j=1,...,h$;
(e) for any θ and θ^*, $\left\|g_j^{(2)}(X_i,\theta)-g_j^{(2)}(X_i,\theta^*)\right\|\le L_j(X_i)\,l_j(\|\theta-\theta^*\|)$, for some measurable function L_j of X_i such that $\sup_n\mathbb{E}_n(L_j(X_i))<\infty$, and $l_j(y)\downarrow 0$ as $y\downarrow 0$.

Assumption 3 *(a) For each θ, $Q_n(\theta)\xrightarrow{p}Q(\theta)$ and $J_n(\theta)\xrightarrow{p}J(\theta)$. (b) For each θ, $\frac{1}{n}\sum_{i=1}^n g_j^{(2)}(X_i,\theta)\xrightarrow{p}(\lim_{n\longrightarrow\infty}\ \mathbb{E}_n[g_j^{(2)}(X_i,\theta)])$. (c) $Z_n\Longrightarrow Z$, where $Z\sim\mathcal{N}(0,J-M'\nu_0\nu_0'M)$.*

2.2 Negligible Remainder

Lemma 5 *Suppose Assumptions 1 to 1 are satisfied, then for all $\gamma_n\longrightarrow 0$*

$$\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\le\gamma_n}\frac{|\mathcal{R}_n(\beta)|}{(1+\|\sqrt{n}(\beta-\beta_{n,0})\|^2)} = o_p(1), \quad (26)$$

where $\mathcal{R}_n(\beta)$ is the remainder term in (17).

Proof of Lemma 5: By Lemma 1(a) of Andrews (1999), it is sufficient to prove

$$\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\le\gamma_n}\left\|G_n^{*(2)}(\beta)-G_n^{*(2)}(\beta_{n,0})\right\| = o_p(1),$$

for every sequence $\gamma_n\longrightarrow 0$. $G_n^{*(2)}$ is defined in (21). To verify this sufficient condition we will subsequently show that

(i) $\sup_{\beta \in \mathcal{B}_n : \|\beta - \beta_{n,0}\| \leq \gamma_n} \left\| G_n^{*(2)}(\beta)_{\theta\theta'} - G_n^{*(2)}(\beta_{n,0})_{\theta\theta'} \right\| = o_p(1)$,

(ii) $\sup_{\beta \in \mathcal{B}_n : \|\beta - \beta_{n,0}\| \leq \gamma_n} \left\| G_n^{*(2)}(\beta)_{\lambda\theta'} - G_n^{*(2)}(\beta_{n,0})_{\lambda\theta'} \right\| = o_p(1)$,

(iii) $\sup_{\beta \in \mathcal{B}_n : \|\beta - \beta_{n,0}\| \leq \gamma_n} \left\| G_n^{*(2)}(\beta)_{\lambda\lambda'} - G_n^{*(2)}(\beta_{n,0})_{\lambda\lambda'} \right\| = o_p(1)$.

We begin by showing that

$$\sup_{\beta \in \mathcal{B}_n} \left| \frac{1}{1 + \lambda' g(X_i, \theta)} \right| = O_p(1). \tag{27}$$

For any given $0 < \delta < \frac{1}{2}$, set $K = \frac{1}{1-\delta}$. Then, since $\sup_{1 \leq i \leq n,\ \beta \in \mathcal{B}_n} |\lambda' g(X_i, \theta)| \leq \delta$ implies $\sup_{1 \leq i \leq n,\ \beta \in \mathcal{B}_n} \left| \frac{1}{1+\lambda' g(X_i,\theta)} \right| \leq K$,

$$P\left\{ \sup_{1 \leq i \leq n,\ \beta \in \mathcal{B}_n} \left| \frac{1}{1 + \lambda' g(X_i, \theta)} \right| > K \right\} \leq P\left\{ \sup_{1 \leq i \leq n,\ \beta \in \mathcal{B}_n} |\lambda' g(X_i, \theta)| > \delta \right\} \longrightarrow 0,$$

which proves (27). The convergence result for the upper bound can be deduced from Lemma 1.

(i) Notice that

$$\begin{aligned}
& \sup_{\beta \in \mathcal{B}_n : \|\beta - \beta_{n,0}\| \leq \gamma_n} \left\| \frac{1}{n} \sum_{i=1}^{n} \left(\frac{\lambda_j g_j^{(2)}(X_i, \theta)}{1 + \lambda' g(X_i, \theta)} \right) \right\| \\
\leq & \sup_{\lambda \in \Lambda_n^\zeta} |\lambda_j| \left(\sup_{\beta \in \mathcal{B}_n, 1 \leq i \leq n} \left| \frac{1}{1 + \lambda' g(X_i, \theta)} \right| \right) \left(\sup_{\theta \in \Theta} \frac{1}{n} \sum \left\| g_j^{(2)}(X_i, \theta) \right\| \right) \\
= & O(n^{-\zeta}) O_p(1) O_p(1) = o_p(1),
\end{aligned}$$

where the last inequality holds by the definition of Λ_n^ζ, (27) and (5). Moreover,

$$\begin{aligned}
& \sup_{\beta \in \mathcal{B}_n : \|\beta - \beta_{n,0}\| \leq \gamma_n} \left\| \frac{1}{n} \sum_{i=1}^{n} \left(\frac{g^{(1)}(X_i, \theta)' \lambda \lambda' g^{(1)}(X_i, \theta)}{(1 + \lambda' g(X_i, \theta))^2} \right) \right\| \\
\leq & \sup_{\lambda \in \Lambda_n^\zeta} \|\lambda\|^2 \left(\sup_{\beta \in \mathcal{B}_n,\ 1 \leq i \leq n} \frac{1}{(1 + \lambda' g(X_i, \theta))^2} \right) \left(\sup_{\theta \in \Theta} \frac{1}{n} \sum_{i=1}^{n} \left\| g^{(1)}(X_i, \theta) \right\| \right) \\
= & O\left(n^{-2\zeta}\right) O_p(1) O_p(1) = o_p(1).
\end{aligned}$$

The last inequality holds by the definition of Λ_n^ζ, (27) and (5).

(ii) Apply the triangle inequality to

$$\begin{aligned}
&\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\leq\gamma_n}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(\frac{g^{(1)}(X_i,\theta)}{1+\lambda' g(X_i,\theta)}-g^{(1)}(X_i,\theta_0)\right)\right\| \\
\leq\;& \sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\leq\gamma_n}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(\frac{g^{(1)}(X_i,\theta)}{1+\lambda' g(X_i,\theta)}-g^{(1)}(X_i,\theta)\right)\right\| \\
&+\sup_{\theta\in\Theta}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(g^{(1)}(X_i,\theta)-\mathbb{E}_n\left[g^{(1)}(X_i,\theta)\right]\right)\right\| \\
&+\sup_{\theta\in\Theta:\|\theta-\theta_0\|\leq\gamma_n}\left\|\mathbb{E}_n\left[g^{(1)}(X_i,\theta)\right]-\mathbb{E}_n\left[g^{(1)}(X_i,\theta_0)\right]\right\| \\
&+\left\|\frac{1}{n}\sum_{i=1}^{n}\left(g^{(1)}(X_i,\theta_0)-\mathbb{E}_n\left[g^{(1)}(X_i,\theta_0)\right]\right)\right\| \\
=\;& I_d+o_p(1)+o_p(1)+o_p(1),
\end{aligned}$$

where the last equality holds by (5) and (4). Next,

$$\begin{aligned}
I_d &\leq \sup_{\beta\in\mathcal{B}_n}|\lambda' g(X_i,\theta)|\left(\sup_{\beta\in\mathcal{B}_n}\left|\frac{1}{1+\lambda' g(X_i,\theta)}\right|\right)\left(\sup_{\theta\in\Theta}\frac{1}{n}\sum_{i=1}^{n}\left\|g^{(1)}(X_i,\theta)\right\|\right) \\
&= o_p(1)\,O_p(1)\,O_p(1)\,O_p(1)=o_p(1)
\end{aligned}$$

by Lemma 1, (27), and (5). Moreover,

$$\begin{aligned}
&\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\leq\gamma_n}\left\|\frac{1}{n}\sum_{i=1}^{n}\frac{g(X_i,\theta)}{1+\lambda' g(X_i,\theta)}\frac{\lambda' g^{(1)}(X_i,\theta)}{1+\lambda' g(X_i,\theta)}\right\| \\
\leq\;& \sup_{\lambda\in\Lambda_n^{\zeta}}\|\lambda\|\left(\sup_{\beta\in\mathcal{B}_n,1\leq i\leq n}\frac{1}{(1+\lambda' g(X_i,\theta))^2}\right)\left(\frac{1}{n}\sum_{i=1}^{n}\sup_{\theta\in\Theta}\|g(X_i,\theta)\|^2\right)^{1/2} \\
&\times\left(\frac{1}{n}\sum_{i=1}^{n}\sup_{\theta\in\Theta}\left\|g^{(1)}(X_i,\theta)\right\|^2\right)^{1/2} \\
=\;& O\left(n^{-\zeta}\right)O_p(1)\,O_p(1)=o_p(1).
\end{aligned}$$

(iii) Similar as before, we have

$$\begin{aligned}
&\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\le\gamma_n}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(\frac{g(X_i,\theta)\,g(X_i,\theta)'}{(1+\lambda'g(X_i,\theta))^2}-g(X_i,\theta_0)\,g(X_i,\theta_0)'\right)\right\| \\
\le&\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\le\gamma_n}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(\frac{g(X_i,\theta)\,g(X_i,\theta)'}{(1+\lambda'g(X_i,\theta))^2}-g(X_i,\theta)\,g(X_i,\theta)'\right)\right\| \\
&+\sup_{\Theta}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(g(X_i,\theta)\,g(X_i,\theta)'-I\!E_n\left[g(X_i,\theta)\,g(X_i,\theta)'\right]\right)\right\| \\
&+\sup_{\Theta}\left\|I\!E_n\left[g(X_i,\theta)\,g(X_i,\theta)'\right]-I\!E_n\left[g(X_i,\theta_0)\,g(X_i,\theta_0)'\right]\right\| \\
&+\sup_{\Theta}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(g(X_i,\theta_0)\,g(X_i,\theta_0)'-I\!E_n\left[g(X_i,\theta_0)\,g(X_i,\theta_0)'\right]\right)\right\| \\
=&\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\le\gamma_n}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(\frac{g(X_i,\theta)\,g(X_i,\theta)'}{(1+\lambda'g(X_i,\theta))^2}-g(X_i,\theta)\,g(X_i,\theta)'\right)\right\|+o_p(1).
\end{aligned}$$

Next,

$$\begin{aligned}
&\sup_{\beta\in\mathcal{B}_n:\|\beta-\beta_{n,0}\|\le\gamma_n}\left\|\frac{1}{n}\sum_{i=1}^{n}\left(\frac{g(X_i,\theta)\,g(X_i,\theta)'}{(1+\lambda'g(X_i,\theta))^2}-g(X_i,\theta)\,g(X_i,\theta)'\right)\right\| \\
\le&\sup_{\beta\in\mathcal{B}_n,1\le i\le n}|\lambda'g(X_i,\theta)|\left(\sup_{\beta\in\mathcal{B}_n,1\le i\le n}\frac{1}{|1+\lambda'g(X_i,\theta)|}\right) \\
&\times\left(\sup_{\beta\in\mathcal{B}_n,1\le i\le n}\frac{1}{|1+\lambda'g(X_i,\theta)|}+1\right)\left(\sup_{\theta\in\Theta}\frac{1}{n}\sum_{i=1}^{n}\|g(X_i,\theta)\|^2\right) \\
=&\;o_p(1)\,O_p(1)\,O_p(1)\,O_p(1)=o_p(1). \quad\blacksquare
\end{aligned}$$

2.3 $\sqrt{n}$ Consistency

Theorem 2 *Suppose Assumptions 1 – 3 are satisfied. Then, (i)* $\sqrt{n}(\tilde\beta_{nq}-\beta_{n,0})=O_p(1)$, *(ii)* $\sqrt{n}(\hat\beta_n-\beta_{n,0})=O_p(1)$, *(iii)* $nG_n^*(\hat\beta_n)=nG_{nq}^*(\hat\beta_n)+o_p(1)$, *(iv)* $nG_{nq}^*(\hat\beta_n)=nG_{nq}^*(\tilde\beta_{nq})+o_p(1)$, *and (v)* $nG_n^*(\hat\beta_n)=nG_{nq}^*(\tilde\beta_{nq})+o_p(1)$.

Theorem 2 establishes that $\hat\beta_n$ and $\tilde\beta_{nq}$ are $\sqrt{n}$-consistent. Moreover, the theorem states that the discrepancy between $G_n^*(\beta)$ evaluated at $\hat\beta_n$ and $G_{nq}^*(\beta)$ evaluated at $\tilde\beta_{nq}$ vanishes. Thus, the large-sample behavior of likelihood ratios can be approximated by the behavior of $G_{nq}^*(\tilde\beta_{nq})$. Let

$$\hat b=[\hat\phi',\hat l'(\hat\phi)]'\quad\text{and}\tilde b_q=[\tilde\phi_q',\tilde l_q'(\tilde\phi_q)]'$$

be re-scaled versions of $\hat\beta_n$ and $\tilde\beta_{nq}$. To prove the theorem, we will introduce a third estimator

$$\hat b_q=[\hat\phi_q',\hat l_q'(\hat\phi_q)]'$$

where

$$\hat l_q(\phi)=\operatorname{argmax}_{l\in L_n(\phi)}\,\mathcal{G}_{nq}^*(\phi,l),\quad \hat\phi_q=\operatorname{argmin}_{\phi\in\Phi_n}\,\mathcal{G}_{nq}^*(\phi,\hat l_q(\phi)).$$

$\hat{b}_q$ is based on the quadratic approximation of the objective function, but the domains of ϕ and l are restricted. In slight abuse of notation we let $B_n = \Phi_n(u_0) \otimes L_n$.

Proof of Theorem 2: (i) Follows from Lemma 7.

(ii) According to Lemma 2, $\hat{\lambda}(\hat{\theta}, \hat{\nu}) = O_p(n^{-1/2})$. It remains to show that

$$\hat{\phi} = \left[\sqrt{n}(\hat{\theta} - \theta_{n,0})',\ u'_{n,0} + \sqrt{n}(\hat{\nu} - \nu_{n,0})' \right]'$$

is stochastically bounded. The saddlepoint property implies that

$$0 = \mathcal{G}^*_n(\hat{\phi}, 0) \leq \mathcal{G}^*_n(\hat{\phi}, \hat{l}(\hat{\phi})) \leq \mathcal{G}^*_n(0, \hat{l}(0)). \tag{28}$$

Then using the quadratic approximation (17), the bound for the remainder term given in Lemma 5 and the definition of $\hat{l}$ and $\hat{\phi}$ we obtain

$$\begin{aligned}
\mathcal{G}^*_n(\hat{\phi}, \hat{l}(\hat{\phi})) &= \mathcal{G}^*_{nq}(\hat{\phi}, \hat{l}(\hat{\phi})) + (1 + \|\hat{\phi} - \phi_{n,0}\|^2 + \|\hat{l}(\hat{\phi})\|^2) o_p(1) \qquad (29) \\
&= \frac{1}{2}(Z_n - R'_n(\hat{\phi} - \phi_{n,0}))' J_n^{-1} (Z_n - R'_n(\hat{\phi} - \phi_{n,0})) \\
&\quad - \frac{1}{2}(\hat{l}(\hat{\phi}) - J_n^{-1}[Z_n - R'_n(\hat{\phi} - \phi_{n,0})])' J_n (\hat{l}(\hat{\phi}) - J_n^{-1}[Z_n - R'_n(\hat{\phi} - \phi_{n,0})]) \\
&\quad + (1 + \|\hat{\phi} - \phi_{n,0}\|^2 + \|\hat{l}(\hat{\phi})\|^2) o_p(1) \\
&= \frac{1}{2}(Z_n - R'_n(\hat{\phi} - \phi_{n,0}))' J_n^{-1} (Z_n - R'_n(\hat{\phi} - \phi_{n,0})) + (1 + \|\hat{\phi} - \phi_{n,0}\|^2 + \|\hat{l}(\hat{\phi})\|^2) o_p(1),
\end{aligned}$$

where $\phi_{n,0} = [0, u'_{n,0}]'$. The last equality is a consequence of Lemma 8. Similarly, we can deduce from Lemmas 2, 5, and Assumptions 1 and 3 that

$$\mathcal{G}^*_n(0, \hat{l}(0)) = -\frac{1}{2}\hat{l}\,(0)'\, J_n \hat{l}\,(0) + Z'_n \hat{l}\,(0) + (1 + \|\hat{l}(0)\|^2) o_p(1) = O_p\,(1)\,. \tag{30}$$

Hence, from (28), (29), and (30) we obtain the inequality

$$0 \leq \frac{1}{2}(Z_n + o_p(1) - R'_n(\hat{\phi} - \phi_{n,0}))' J_n^{-1} (Z_n + o_p(1) - R'_n(\hat{\phi} - \phi_{n,0})) \leq O_p(1). \tag{31}$$

Notice that $Z_n + o_p(1) = O_p\,(1)$. According to Assumption 1, R_n is full rank and J_n is positive definite w.p.a. 1. Therefore, (31) implies that $\hat{\phi} - \phi_{n,0}$ is stochastically bounded.

(iii) We deduce from Lemma 5 and Part (ii) that

$$\begin{aligned}
nG^*_n(\hat{\beta}_n) &= \mathcal{G}^*_{nq}(\sqrt{n}(\hat{\beta}_n - \beta_{n,0})) + (1 + \|\sqrt{n}(\hat{\beta}_n - \beta_{n,0})\|^2) o_p(1) \\
&= nG^*_{nq}(\hat{\beta}_n) + O_p(1) o_p(1).
\end{aligned}$$

(iv) We proceed by establishing $o_p(1)$ bounds for $nG^*_{nq}(\hat{\beta}_n) - nG^*_{nq}(\tilde{\beta}_{nq})$.

We begin with the upper bound. Using (iii) we can rewrite the differential as

$$\begin{aligned}
nG^*_{nq}(\hat{\beta}_n) - nG^*_{nq}(\tilde{\beta}_{nq}) &= \mathcal{G}^*_n(\hat{\phi}, \hat{l}(\hat{\phi})) + o_p(1) - \mathcal{G}^*_{nq}(\tilde{\phi}_q, \tilde{l}_q(\tilde{\phi}_q)) \qquad (32) \\
&\leq \mathcal{G}^*_n(\tilde{\phi}_q, \hat{l}(\tilde{\phi}_q)) - \mathcal{G}^*_{nq}(\tilde{\phi}_q, \hat{l}(\tilde{\phi}_q)) + o_p(1).
\end{aligned}$$

Replacing $\hat{\phi}$ by $\hat{\phi}_q$ raises $\mathcal{G}_n^*$, whereas substituting $\tilde{l}_q$ with $\hat{l}$ lowers $\mathcal{G}_{nq}^*$. Using Lemma 5 the first term on the right-hand side of (32) can be rewritten as

$$\begin{aligned}\mathcal{G}_n^*(\hat{\phi}_q, \hat{l}(\hat{\phi}_q)) &= \mathcal{G}_{nq}^*(\hat{\phi}_q, \hat{l}(\hat{\phi}_q)) + o_p(1)\left(1 + \|\hat{\phi}_q - \phi_{n,0}\|^2 + \|\hat{l}(\hat{\phi}_q)\|^2\right) \\ &= \mathcal{G}_{nq}^*(\hat{\phi}_q, \hat{l}(\hat{\phi}_q)) + o_p(1).\end{aligned} \tag{33}$$

The second equality in (33) is a consequence of Lemmas 2 and 7. According to Lemma 8

$$\hat{l}(\bar{\phi}) = (J_n + o_p(1))^{-1}[Z_n - (R_n' + o_p(1))(\bar{\phi} - \phi_{n,0})]$$

for $\bar{\phi} = O_p(1)$. Hence,

$$\hat{l}(\tilde{\phi}_q) - \hat{l}(\hat{\phi}_q) = -(J_n + o_p(1))^{-1}[(R_n' + o_p(1))](\tilde{\phi}_q - \hat{\phi}_q) = o_p(1)$$

by Lemma 7. Since $\mathcal{G}_{nq}^*(\phi, l)$ is continuous in its arguments we can now express the second term on the right-hand side of (32) as

$$\mathcal{G}_{nq}^*(\tilde{\phi}_q, \hat{l}(\tilde{\phi}_q)) = \mathcal{G}_{nq}^*(\hat{\phi}_q, \hat{l}(\hat{\phi}_q)) + o_p(1) \tag{34}$$

Plugging (33) and (34) into (32) we obtain the upper bound

$$nG_{nq}^*(\hat{\beta}_n) - nG_{nq}^*(\tilde{\beta}_{nq}) \leq o_p(1).$$

Using similar arguments, we can establish a lower bound as follows:

$$\begin{aligned}nG_{nq}^*(\hat{\beta}_n) - nG_{nq}^*(\tilde{\beta}_{nq}) &= \mathcal{G}_n^*(\hat{\phi}, \hat{l}(\hat{\phi})) - \mathcal{G}_{nq}^*(\tilde{\phi}_q, \tilde{l}_q(\tilde{\phi}_q)) + o_p(1) \\ &\geq \mathcal{G}_n^*(\hat{\phi}, \hat{l}_q(\hat{\phi})) - \mathcal{G}_{nq}^*(\hat{\phi}, \tilde{l}_q(\hat{\phi})) + o_p(1) \\ &= \mathcal{G}_n^*(\hat{\phi}, \hat{l}_q(\hat{\phi})) - \mathcal{G}_{nq}^*(\hat{\phi}, \hat{l}_q(\hat{\phi})) + o_p(1) \\ &= o_p(1)\end{aligned}$$

which proves (iv). ■

(v) Follows from parts (iii) and (iv).

2.3.1 Technical Lemmas

Lemma 6 *Suppose Assumptions 1 to 3 are satisfied. Then,* $\tilde{b}_q$ *exists uniquely w.p.a. 1.*

Proof of Lemma 6: The subsequent statements are true w.p.a. 1. Notice that $\bar{\mathcal{G}}_{nq}^*(\phi)$, defined in (25), is strictly convex function of ϕ because $R_n' = [-Q_n', M']$ is a full rank matrix under Assumption 1(c) and J_n^{-1} is positive definite. Hence, $R_n J_n^{-1} R_n'$ is a positive definite matrix. Moreover, the domain Φ is convex. Therefore, $\tilde{\phi}_q$ is unique. Finally, from (24) we deduce that $\tilde{l}_q$ exists uniquely. ■

Lemma 7 *Suppose Assumptions 1 to 3 are satisfied. Then* *(i)* $\tilde{b}_q = O_p(1)$,

(ii) $\hat{b}_q = \tilde{b}_q + o_p(1)$.

Proof of Lemma 7:

Proof of (i): We will show that $\tilde{\phi}_q = O_p(1)$. For notational simplicity, denote

$$A_{1n} = R_n J_n^{-1} R_n', \; A_{2n} = A_{1n}^{-1} R_n J_n^{-1} Z_n, \text{ and } A_{3n} = Z_n' J_n^{-1} Z_n - A_{2n}' A_{1n} A_{2n},$$

and write the concentrated quadratic objective function (25) as

$$\bar{\mathcal{G}}_{nq}^*(\phi) = \frac{1}{2}(\phi - \phi_{n,0} + A_{2n})' A_{1n} (\phi - \phi_{n,0} + A_{2n}) + \frac{1}{2} A_{3n}.$$

Observe that J_n, R_n, and Z_n converge weakly according to Assumptions 1 and 3. Moreover based on Assumption 1, A_{1n} is positive definite w.p.a. 1. Let

$$\bar{\phi}_q = \text{argmin}_{\phi \in \mathbb{R}^{m+h_2}} \bar{\mathcal{G}}_{nq}^*(\phi) = \phi_{n,0} - A_{2n} = O_p(1).$$

Notice that $\tilde{\phi}_q$ is the projection of $\bar{\phi}_q$ onto the set $\Phi(u_0)$ with respect to the inner product $\langle x, y \rangle = x' A_{1n} y$. Then,

$$\|\tilde{\phi}_q\| \leq \lambda_{min}^{-1}(A_{1n}) \langle \tilde{\phi}_q, \tilde{\phi}_q \rangle^{1/2} \leq \lambda_{min}^{-1}(A_{1n}) \langle \bar{\phi}_q, \bar{\phi}_q \rangle^{1/2} = O_p(1)$$

where $\lambda_{min}(A_{1n})$ denotes the smallest eigenvalue of A_{1n} and is strictly positive w.p.a. 1. Finally, from (24) we can deduce that $\tilde{l}_q(\tilde{\phi}_q) = O_p(1)$.

Proof of (ii): According to Lemma 6 the saddlepoint problem $\min_{\phi \in \Phi(u_0)} \max_{l \in \mathbb{R}^h} \mathcal{G}_{nq}^*(\phi, l)$ has a unique solution $\tilde{b}_q$ on the domain $B = \Phi(u_0) \otimes \mathbb{R}^h$. Since $B_n \subset B$ for any $\epsilon > 0$

$$\begin{aligned} P\left\{\|\hat{b}_q - \tilde{b}_q\| > \epsilon\right\} &\leq P\left\{\tilde{b}_q \in B \backslash B_n\right\} \\ &\leq P\{\tilde{b}_q \in B \backslash (\Phi_n(u_0) \otimes \sqrt{n}\Lambda_n^\zeta)\} + o(1), \end{aligned}$$

where the $o(1)$ term in the last line holds by Lemma 1(ii). The set $\sqrt{n}\Lambda_n^\zeta$ consists of the elements in Λ_n^ζ multiplied by $\sqrt{n}$ and expands to $\mathbb{R}^h$ because $\zeta < 1/2$. Since θ_0 is in the interior of Θ, the first m ordinates of $\Phi_n(u_0)$ expand to $\mathbb{R}^m$. Ordinate $m+j$ expands to $\mathbb{R}$ if $u_{0,j} = \infty$ and to $\mathbb{R}^+$ otherwise. Since $\tilde{b}_q = O_p(1)$, we deduce $P\{\tilde{b}_q \in B \backslash (\Phi_n(u_0) \otimes \sqrt{n}\Lambda_n^\zeta)\} = o(1)$. Therefore $\hat{b}_q = \tilde{b}_q + o_p(1)$, as required. ■

Lemma 8 *Suppose that Assumptions 1 to 3 are satisfied. Let $\bar{\theta} \in \Theta$ and $\bar{\nu} \geq 0$ be sequences such that $\bar{\theta} - \theta_{n,0} \xrightarrow{p} 0$ and $\bar{\nu} - \nu_{n,0} \xrightarrow{p} 0$. Let $\hat{l}(\bar{\phi}) = \sqrt{n}\hat{\lambda}(\bar{\theta}, \bar{\nu})$, and $\bar{\phi} = [\bar{s}', \bar{u}']$, where $\bar{s} = \sqrt{n}(\bar{\theta} - \theta_{n,0})$ and $\bar{u} = u_{n,0} + \sqrt{n}(\bar{\nu} - \nu_{n,0})$. Then*

$$0 = Z_n - (R_n' + o_p(1))(\bar{\phi} - \phi_{n,0}) - (J_n + o_p(1))\hat{l}(\bar{\phi}).$$

Proof of Lemma 8: In view of Lemmas 1(ii) and 2, we deduce that $\hat{\lambda}(\bar{\theta}, \bar{v})$ is in the interior of $\hat{\Lambda}(\bar{\theta})$ w.p.a. 1. Hence, $\hat{\lambda}$ satisfies the first-order conditions associated with $\max_{\lambda \in \hat{\Lambda}(\bar{\theta})} G_n^* \left(\bar{\theta}, \bar{\nu}, \lambda\right)$:

$$0 = \frac{1}{n} \sum_{i=1}^{n} \frac{g(X_i, \bar{\theta})}{1 + \hat{\lambda}' g(X_i, \bar{\theta})} - M' \bar{\nu}.$$

We now apply the mean-value theorem and multiply by $\sqrt{n}$:

$$0 = \sqrt{n} G_n^{*(1)}(\beta_{n,0})_\lambda + G_n^{*(2)}(\beta_*)_{\lambda\theta'} \bar{s} - M'(\bar{u} - u_{n,0}) + G_n^{*(2)}(\beta_*)_{\lambda\lambda'} \hat{l},$$

where β_* lies on the line joining $\beta_{n,0}$ and $\bar{\beta} = [\bar{\theta}', \bar{\nu}', \hat{\lambda}(\bar{\theta}, \bar{\nu})']'$. The matrices $G_n^{*(1)}(\beta)$ and $G_n^{*(2)}(\beta)$ and their partitions are defined in (19) and (21). Using the same arguments as in the proof of Lemma 5 and the definitions of J_n, Q_n, R_n, and Z_n we obtain the desired result. ■