# A Appendix

**Lemma 2.** (U-Statistic with Estimated Parameter) *Let* $\{Z_i\}_{i=1}^{N}$ *be a simple random sample drawn from some population* $F_Z$ *and* $\phi(Z_i, Z_j; \beta, \gamma)$ *be a function from* $\mathbb{Z} \times \mathbb{Z}$ *to* $\mathbb{R}^J$ *indexed by* $\beta \in \mathbb{B}$ *and* $\gamma \in \mathbb{C}$ *(with* $\mathbb{B}$ *and* $\mathbb{C}$ *compact subsets of* $\mathbb{R}^{\dim(\beta)}$ *and* $\mathbb{R}^{\dim(\gamma)}$ *respectively). Suppose that* $\phi(z_1, z_2; \beta, \gamma)$ *is twice continuously differentiable in* $\gamma$ *for all* $z_1, z_2 \in \mathbb{Z} \times \mathbb{Z}$ *with*

$$\mathbb{E}\left[\left\|\phi(Z_1, Z_2; \beta, \gamma)\right\|_2\right] < \infty \tag{117}$$

$$\mathbb{E}\left[\left\|\frac{\partial \phi(Z_1, Z_2; \beta, \gamma)}{\partial \gamma'}\right\|_F\right] < \infty \tag{118}$$

$$\mathbb{E}\left[\left\|\frac{\partial}{\partial \gamma'}\left\{\frac{\partial \phi(Z_1, Z_2; \beta, \gamma)}{\partial \gamma_p}\right\}\right\|_F\right] < \infty, \quad p = 1, \ldots, \dim(\gamma). \tag{119}$$

*Then, for* $\hat{\gamma}$ *a* $\sqrt{N}$*-consistent estimate of* $\gamma_0$*, and defining* $\bar{\phi}_N(\beta, \gamma) \overset{def}{\equiv} \binom{N}{2}^{-1} \sum_{i=1}^{N} \sum_{j=i+1}^{N-1} \phi(Z_i, Z_j; \beta, \gamma)$ *and* $\Phi(\beta, \gamma) \overset{def}{\equiv} \mathbb{E}[\phi(Z_1, Z_2; \beta, \gamma)]$*, we have*

$$\sqrt{N}\left[\bar{\phi}_N(\beta, \hat{\gamma}) - \Phi(\beta, \gamma_0)\right] = \frac{2}{\sqrt{N}} \sum_{i=1}^{N} \psi_0(Z_1; \beta, \gamma_0) + \Gamma_{0,\beta\gamma}(\beta) \sqrt{N}(\hat{\gamma} - \gamma_0) + o_p(1) \tag{120}$$

*where* $\phi_1(z; \beta, \gamma) = \mathbb{E}[\phi(z, Z_1; \beta, \gamma)]$ *and*

$$\begin{aligned} \psi_0(Z_1; \beta, \gamma) &= \phi_1(Z_1; \beta, \gamma) - \Phi(\beta, \gamma) \\ \Gamma_{0,\beta\gamma}(\beta) &= \mathbb{E}\left[\frac{\partial \phi(Z_1, Z_2; \beta, \gamma_0)}{\partial \gamma'}\right]. \end{aligned}$$

**Proof of Lemma 2**

A Taylor expansion of $\bar{\phi}_N(\beta, \hat{\gamma})$ in $\hat{\gamma}$ about $\gamma_0$ yields, after some re-arrangement and centering,

$$\sqrt{N}\left[\bar{\phi}_N(\beta, \hat{\gamma}) - \Phi(\beta, \gamma_0)\right] = \sqrt{N}\left[\bar{\phi}_N(\beta, \gamma_0) - \Phi(\beta, \gamma_0)\right] + \Gamma_{N,\beta\gamma}(\beta, \bar{\gamma}) \sqrt{N}(\hat{\gamma} - \gamma_0), \tag{121}$$

with $\bar{\gamma}$ a mean value between $\hat{\gamma}$ and $\gamma_0$ which may vary across the rows of the Hessian $\Gamma_{N,\beta\gamma}(\beta, \gamma) \overset{def}{\equiv} \frac{\partial \bar{\phi}_N(\beta, \gamma)}{\partial \gamma'}$. Next recall the definition of the $L_{2,1}$ norm:

$$\|\mathbf{A}\|_{2,1} = \sum_{j=1}^{n} \left[\sum_{i=1}^{m} |a_{ij}|^2\right]^{1/2}. \tag{122}$$

The mean value theorem, as well as compatibility of the Frobenius matrix norm with the Euclidean vector norm, gives for any $\gamma$ and $\gamma^*$ both in $\mathbb{C}$,

$$\left\|\frac{\partial\bar{\phi}_N(\beta,\gamma)}{\partial\gamma'}-\frac{\partial\bar{\phi}_N(\beta,\gamma^*)}{\partial\gamma'}\right\|_{2,1}\leq\sum_{p=1}^{\dim(\gamma)}\left\|\frac{\partial}{\partial\gamma'}\left\{\frac{\partial\bar{\phi}_N(\beta,\gamma)}{\partial\gamma_p}\right\}\right\|_F\|\gamma-\gamma_*\|_2\,. \tag{123}$$

Observe that $\frac{\partial}{\partial\gamma'}\left\{\frac{\partial\bar{\phi}_N(\beta,\gamma)}{\partial\gamma_p}\right\}$ is a matrix of U-statistics with kernels whose first moments are finite (by condition 106 above). By Serfling (1980, Theorem 5.4A) these U-statistics converge in probability and hence, from (123)

$$\left\|\frac{\partial\bar{\phi}_N(\beta,\gamma)}{\partial\gamma'}-\frac{\partial\bar{\phi}_N(\beta,\gamma^*)}{\partial\gamma'}\right\|_{2,1}\leq O_p(1)\cdot\|\gamma-\gamma_*\|_2\,.$$

This condition, as well compactness of $\mathbb{C}$, continuity of $\frac{\partial\bar{\phi}_N(\beta,\gamma)}{\partial\gamma}$ in $\gamma$, and condition (118), allow for an application of Lemma 2.9 in Newey & McFadden (1994) such that $\sup_{\gamma\in\mathbb{C}}\left\|\frac{\partial\bar{\phi}_N(\beta,\gamma)}{\partial\gamma'}-\Gamma_{\beta\gamma}(\beta,\gamma)\right\|_F\xrightarrow{p}0$ with $\Gamma_{\beta\gamma}(\beta,\gamma)=\mathbb{E}\left[\frac{\partial\phi(Z_1,Z_2;\beta,\gamma)}{\partial\gamma'}\right]$. This, along with consistency of $\hat{\gamma}$ for $\gamma_0$, is enough to ensure that $\frac{\partial\bar{\phi}_N(\beta,\bar{\gamma})}{\partial\gamma'}\xrightarrow{p}\Gamma_{0,\beta\gamma}(\beta)$. Equation (120) then follows by observing that $\bar{\phi}_N(\beta,\gamma_0)-\Phi(\beta,\gamma_0)$ is a vector of mean zero U-Statistics with Hájek projections equal to the corresponding components of the first term to the right of the equality in (120) (see, for example, Theorem 5.3.3. of Serfling (1980) and invoke condition (117) above). See Mao (2018, Lemma S1) for a related Lemma.

### Order of variances and covariances for $p^{th}$ order induced subgraph frequencies

Here I present the order of the covariance between empirical subgraph frequencies, where the subgraph is of arbitrary order. For general $p^{th}$-order graphlets $R$ and $S$ we have that

$$\begin{aligned}\mathbb{C}(P_N(R),P_N(S))=&\binom{N}{p}^{-2}\sum_{q=1}^{p}\binom{N}{p}\binom{p}{q}\binom{N-p}{p-q}\Sigma_q(R,S)\\=&\binom{N}{p}^{-2}\sum_{q=1}^{p}\binom{N}{p}\binom{p}{q}\binom{N-p}{p-q}\Xi(\mathcal{W}_{q,R,S})\\&-\left[1-\frac{(N-p)!^2}{N!\,(N-2p)!}\right]P(R)\,P(S)\,.\end{aligned} \tag{124}$$

Normalizing by $\rho_N$ raised to the number of edges in $R$ and $S$, respectively $\rho_N^{e(R)}$ and $\rho_N^{e(S)}$, yields

$$\mathbb{C}\left(\tilde{P}_N(R), \tilde{P}_N(S)\right) = \left\{ \underbrace{\binom{N}{p}^{-2} \sum_{q=1}^{p-1} \binom{N}{p}\binom{p}{q}\binom{N-p}{p-q} \left[\frac{\Xi(\mathcal{W}_{q,R,S})}{\rho_N^{e(R)}\rho_N^{e(S)}}\right]}_{O\left(N^{-q}\rho_N^{-e(R)}\rho_N^{-e(S)}\right)O\left(\Xi\left(\mathcal{W}_{q,R,S}\right)\right)} - \left[1 - \frac{(N-p)!^2}{N!\,(N-2p)!}\right] \tilde{P}(R)\,\tilde{P}(S) \right\}. \tag{125}$$

There are $2p-q$ vertices in each element of $\mathcal{W}_{q,R,S}$.

**Case 1 ($q = 1$):**

If $q = 1$, then $e(W) = e(R) + e(S)$ for all $W \in \mathcal{W}_{q,R,S}$. This gives

$$\begin{aligned} O\left(N^{-q}\rho_N^{-e(R)}\rho_N^{-e(S)}\right) O\left(\Xi\left(\mathcal{W}_{1,R,S}\right)\right) &= O\left(N^{-1}\rho_N^{-e(R)}\rho_N^{-e(S)}\right) O\left(\rho_N^{e(R)}\rho_N^{e(S)}\right) \\ &= O\left(N^{-1}\right). \end{aligned}$$

**Case ($q = p$):**

If $q = p$, then $\Xi(\mathcal{W}_{q,R,S}) = 0$ unless $R = S$. In that case, the "variance case", we have that $e(W) = p$ since $W = R = S$. This gives

$$\begin{aligned} O\left(N^{-q}\rho_N^{-2e(R)}\right) O\left(\Xi\left(\mathcal{W}_{p,R}\right)\right) &= O\left(N^{-p}\rho_N^{-2e(R)}\right) O\left(\rho_N^{e(R)}\right) \\ &= O\left(N^{-p}\rho_N^{-e(R)}\right). \end{aligned}$$

If $R$ is a p-cycle, then $p = e(R)$, yielding the simplification $O\left(N^{-p}\rho_N^{-e(R)}\right) = O\left(\lambda_N^{-p}\right)$.

If $R$ is a tree, then $e(R) = p-1$, yielding the simplification $O\left(N^{-p}\rho_N^{-e(R)}\right) = O\left(N^{-1}\lambda_N^{-(p-1)}\right)$.

**<u>Case $(1 < q < p)$:</u>**

For $q = 2, \ldots, p-1$ we have that $e(W) = e(R) + e(S) - (q-1)$ if $R$ and $S$ are both p-cycles so that

$$\begin{aligned} O\left(N^{-q}\rho_N^{-e(R)}\rho_N^{-e(S)}\right) O\left(Q\left(\mathcal{W}_{q,R,S}\right)\right) &= O\left(N^{-q}\rho_N^{-e(R)}\rho_N^{-e(S)}\right) O\left(\rho_N^{e(R)+e(S)-(q-1)}\right) \\ &= O\left(N^{-q}\rho_N^{-(q-1)}\right) \\ &= O\left(N^{-1}\lambda_N^{-(q-1)}\right). \end{aligned}$$

Whereas we have that $e(W) \geq e(R) + e(S) - (q-1)$ if $R$ and $S$ are both trees, or one is a tree and the other a p-cycle, so that

$$\begin{aligned} O\left(N^{-q}\rho_N^{-e(R)}\rho_N^{-e(S)}\right) O\left(\Xi\left(\mathcal{W}_{q,R,S}\right)\right) &\leq O\left(N^{-q}\rho_N^{-e(R)}\rho_N^{-e(S)}\right) O\left(\rho_N^{e(R)+e(S)-(q-1)}\right) \\ &= O\left(N^{-1}\lambda_N^{-(q-1)}\right). \end{aligned}$$

**Proof of Theorem 3**

Without loss of generality set $i = 1$. By the definition of degree we have that

$$\mathbb{E}\left[D_{1+}^m\right] = \mathbb{E}\left[\left(\sum_{j=2}^{N} D_{1j}\right)^m\right],$$

the multinomial theorem allows us to write the term inside the expectation above as

$$D_{1+}^m = \left(\sum_{j=2}^{N} D_{1j}\right)^m = \sum_{q_2+\cdots+q_N=m} \binom{m}{q_2, q_3, \cdots, q_N} \prod_{j=2}^{N} D_{1j}^{q_j} \tag{126}$$

where $\binom{m}{q_2,q_3,\cdots,q_N} = \frac{m!}{q_2!q_3!\cdots q_N!}$. Since $D_{1j}$ is binary $D_{1j}^{q_j} = D_{1j}$ for all $q_j = 1, 2, \ldots, m$ and zero when $q_j = 0$. This implies that $\prod_{j=2}^{N} D_{1j}^{q_j} = D_{1j_1} \times \cdots \times D_{1j_k}$ for $D_{1j_1}, D_{1j_2}, \ldots, D_{1j_k}$ the set of $1 \leq k \leq m$ link indicators with $q_j \geq 1$. Consider agents $j_1, j_2, \ldots, j_k$, with, say, $q_{j_1} = p_1$, $q_{j_2} = p_2, \ldots, q_{j_k} = p_k$ such that $\mathbf{p} \in \mathcal{P}_{k,m}$, it follows that

$$\prod_{j=2}^{N} D_{1j}^{q_j} = D_{1j_1}^{p_1} \times \cdots \times D_{1j_k}^{p_k}. \tag{127}$$

By the multinomial theorem the coefficient on (127) equals $\frac{m!}{p_1!\times\cdots\times p_k!}$, but since

$$D_{1j_1}^{p_1} \times \cdots \times D_{1j_k}^{p_k} = D_{1j_1}^{p_1^*} \times \cdots \times D_{1j_k}^{p_k^*} = D_{1j_1} \times \cdots \times D_{1j_k}$$

for any $\mathbf{p}, \mathbf{p}^* \in \mathcal{P}_{k,m}$, the coefficient on $D_{1j_1} \times \cdots \times D_{1j_k}$ after combining identical terms in (126) equals $\sum_{\mathbf{p}\in\mathcal{P}_{k,m}} \frac{m!}{p_1!\times\cdots\times p_k!}$. Putting these pieces together yields

$$\mathbb{E}\left[D_{i+}^m\right] = \sum_{k=1}^{m} \left( \sum_{\mathbf{p}\in\mathcal{P}_{k,m}} \frac{m!}{p_1! \times \cdots \times p_k!} \right) \mathbb{E}\left[ \sum_{j_1<\cdots<j_k} D_{ij_1} \times \cdots \times D_{ij_k} \right]$$

The expectations of the summands in $\sum_{j_1<\cdots<j_k} D_{ij_1} \times \cdots \times D_{ij_k}$ are all identical with cardinality $\binom{N-1}{k}$. The assertion follows.

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