# Notes on Linear Panel Model

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## 1 Fixed Effect Model

$$y_{it} = \boldsymbol{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it} \qquad \text{Level 1}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \alpha_i + \begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$
$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i} \qquad \text{Level 2}$$

$$\begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} = \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{pmatrix} + \begin{pmatrix} \boldsymbol{\varepsilon}_1 \\ \vdots \\ \boldsymbol{\varepsilon}_N \end{pmatrix}$$
$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon} \qquad \text{Level 3}$$

where $\alpha_i$ is unobserved heterogeneity, $\boldsymbol{\varepsilon}_i$ is idiosyncratic error, $\boldsymbol{u}_i$ is composite error.

### 1.1 Assumption

#### 1.1.1 Strong/strict exogeneity of regressors

For all $t$,

$$\mathbb{E}(\varepsilon_{it}|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT}) = 0$$

Equivalently,

$$\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{0}$$

### 1.2 OLS estimator is inconsistent and biased

The necessary condition for OLS estimator to be consistent is $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \boldsymbol{0}$.

$$\begin{aligned}
\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) &= \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i|\boldsymbol{X}_i)) \\
&= \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i)) \\
&= \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)) \\
&= \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{e}\alpha_i|\boldsymbol{X}_i) + \boldsymbol{X}_i'\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\boldsymbol{0}}) && \text{because of strict exogeneity} \\
&= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\mathbb{E}(\alpha_i|\boldsymbol{X}_i)) \\
&= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i)
\end{aligned}$$

$\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq 0 \iff \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) \neq \boldsymbol{0}$. Thus, OLS estimator is inconsistent if $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq \boldsymbol{0}$.

The necessary condition for OLS estimator to be unbiased is $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0}$. However, $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{0}) = \boldsymbol{0}$. Thus, $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) \neq \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) \neq \boldsymbol{0}$. As a result, OLS estimator is biased if $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq \boldsymbol{0}$.

$\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) = \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\mathbb{E}(\alpha_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\boldsymbol{0}) = \boldsymbol{0}$. Thus, $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq \boldsymbol{0} \implies \mathbb{E}(\alpha_i|\boldsymbol{X}_i) \neq 0$

OLS estimator of $\boldsymbol{\beta}$ is inconsistent and biased if $\alpha_i$ is correlated with $\boldsymbol{X}_i$ ($\boldsymbol{u}_i$ is also correlated with $\boldsymbol{X}_i$). This is called omitted variable bias. To tackle this, we simply eliminate $\alpha_i$ by using different methods.

## 1.3 Fixed Effect Estimator / Within Estimator

### 1.3.1 Demean operator

$$\boldsymbol{Q} = \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}'$$

This $\boldsymbol{Q}$ is symmetric and idempotent,

$$\begin{aligned}
\boldsymbol{Q}' &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')' \\
&= \boldsymbol{I}_T' - T^{-1}\boldsymbol{e}''\boldsymbol{e}' \\
&= \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' = \boldsymbol{Q}
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{Q}\boldsymbol{Q}' &= \boldsymbol{Q}\boldsymbol{Q} \\
&= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')(\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \boldsymbol{I}_T\boldsymbol{I}_T - \boldsymbol{I}_T T^{-1}\boldsymbol{e}\boldsymbol{e}' - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{I}_T + T^{-1}\boldsymbol{e}\boldsymbol{e}'T^{-1}\boldsymbol{e}\boldsymbol{e}' \\
&= \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' - T^{-1}\boldsymbol{e}\boldsymbol{e}' + T^{-2}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{e}\boldsymbol{e}' \\
&= \boldsymbol{I}_T - 2T^{-1}\boldsymbol{e}\boldsymbol{e}' + T^{-2}\boldsymbol{e}T\boldsymbol{e}' \\
&= \boldsymbol{I}_T - 2T^{-1}\boldsymbol{e}\boldsymbol{e}' + T^{-1}\boldsymbol{e}\boldsymbol{e}' \\
&= \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' = \boldsymbol{Q}
\end{aligned}$$

### 1.3.2 Demean transformed model

$$\begin{aligned}
\boldsymbol{Q}\boldsymbol{y}_i &= \boldsymbol{Q}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i) \\
&= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}\boldsymbol{e}\alpha_i + \boldsymbol{Q}\boldsymbol{\varepsilon}_i \\
&= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{0}\alpha_i + \boldsymbol{Q}\boldsymbol{\varepsilon}_i \\
&= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}\boldsymbol{\varepsilon}_i \qquad \text{Level 2}
\end{aligned}$$

It is because

$$\begin{aligned}
\boldsymbol{Q}\boldsymbol{e} &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')\boldsymbol{e} \\
&= \boldsymbol{I}_T\boldsymbol{e} - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{e} \\
&= \boldsymbol{e} - T^{-1}\boldsymbol{e}T \\
&= \boldsymbol{e} - \boldsymbol{e} = \boldsymbol{0}
\end{aligned}$$

It can be written as $\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)$ because

$$\begin{aligned}
\boldsymbol{Q}\boldsymbol{X}_i &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')\boldsymbol{X}_i \\
&= \boldsymbol{I}_T\boldsymbol{X}_i - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{X}_i \\
&= \boldsymbol{X}_i - T^{-1}\boldsymbol{e}\begin{pmatrix}1 & \cdots & 1\end{pmatrix}\begin{pmatrix}\boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}'\end{pmatrix} \\
&= \boldsymbol{X}_i - \boldsymbol{e}T^{-1}\sum_{t=1}^{T}\boldsymbol{x}_{it}' \\
&= \boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i'
\end{aligned}$$

$$
\begin{aligned}
\boldsymbol{Q}\boldsymbol{y}_i &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')\boldsymbol{y}_i \\
&= \boldsymbol{I}_T\boldsymbol{y}_i - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{y}_i \\
&= \boldsymbol{y}_i - T^{-1}\boldsymbol{e}\begin{pmatrix}1 & \cdots & 1\end{pmatrix}\begin{pmatrix}y_{i1} \\ \vdots \\ y_{iT}\end{pmatrix} \\
&= \boldsymbol{y}_i - \boldsymbol{e}T^{-1}\sum_{t=1}^{T} y_{it} \\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i
\end{aligned}
$$

$\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)$ can be written as

$$
\begin{aligned}
\begin{pmatrix}y_{i1} \\ \vdots \\ y_{iT}\end{pmatrix} - \begin{pmatrix}1 \\ \vdots \\ 1\end{pmatrix}\bar{y}_i &= (\begin{pmatrix}\boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}'\end{pmatrix} - \begin{pmatrix}1 \\ \vdots \\ 1\end{pmatrix}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\begin{pmatrix}\varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT}\end{pmatrix} - \begin{pmatrix}1 \\ \vdots \\ 1\end{pmatrix}\bar{\varepsilon}_i) \\
\begin{pmatrix}y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i\end{pmatrix} &= \begin{pmatrix}\boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i'\end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix}\varepsilon_{i1} - \bar{\varepsilon}_i \\ \vdots \\ \varepsilon_{iT} - \bar{\varepsilon}_i\end{pmatrix} \\
\begin{pmatrix}y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i\end{pmatrix} &= \begin{pmatrix}(\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)'\end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix}\varepsilon_{i1} - \bar{\varepsilon}_i \\ \vdots \\ \varepsilon_{iT} - \bar{\varepsilon}_i\end{pmatrix} \\
y_{it} - \bar{y}_i &= (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + (\varepsilon_{it} - \bar{\varepsilon}_i) && \text{Level 1}
\end{aligned}
$$

### 1.3.3 OLS estimator of the demean transformed model / Fixed Effect (FE) estimator

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{within}^{ols} &= [\sum_{i=1}^{N}(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{y}_i && \text{Level 2} \\
&= [\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) && \text{Level 1}
\end{aligned}
$$

It is because

$$
\begin{aligned}
(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i') \\
&= (\begin{pmatrix}\boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}'\end{pmatrix} - \begin{pmatrix}1 \\ \vdots \\ 1\end{pmatrix}\bar{\boldsymbol{x}}_i')'(\begin{pmatrix}\boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}'\end{pmatrix} - \begin{pmatrix}1 \\ \vdots \\ 1\end{pmatrix}\bar{\boldsymbol{x}}_i') \\
&= \begin{pmatrix}\boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i'\end{pmatrix}'\begin{pmatrix}\boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i'\end{pmatrix} \\
&= \begin{pmatrix}(\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)'\end{pmatrix}'\begin{pmatrix}(\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)'\end{pmatrix} \\
&= \begin{pmatrix}(\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i) & \cdots & (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)\end{pmatrix}\begin{pmatrix}(\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)'\end{pmatrix} \\
&= \sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'
\end{aligned}
$$

$$
\begin{aligned}
(\boldsymbol{QX}_i)'\boldsymbol{Qy}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i) \\
&= (\begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \bar{\boldsymbol{x}}_i')'(\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \bar{y}_i) \\
&= \begin{pmatrix} \boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i' \end{pmatrix}' \begin{pmatrix} y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i) & \cdots & (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i) \end{pmatrix} \begin{pmatrix} y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i \end{pmatrix} \\
&= \sum_{t=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i)
\end{aligned}
$$

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{within}^{ols} &= [\sum_{i=1}^{N} (\boldsymbol{QX}_i)'\boldsymbol{QX}_i]^{-1} \sum_{i=1}^{N} (\boldsymbol{QX}_i)'\boldsymbol{Qy}_i && \text{Level 2} \\
&= [\sum_{i=1}^{N} (\boldsymbol{X}_i'\boldsymbol{X}_i - \bar{\boldsymbol{x}}_i T \bar{\boldsymbol{x}}_i')]^{-1} \sum_{i=1}^{N} (\boldsymbol{X}_i'\boldsymbol{y}_i - \bar{\boldsymbol{x}}_i T \bar{y}_i) \\
&= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{X}_i - T \sum_{i=1}^{N} \bar{\boldsymbol{x}}_i \bar{\boldsymbol{x}}_i']^{-1} (\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{y}_i - T \sum_{i=1}^{N} \bar{\boldsymbol{x}}_i \bar{y}_i) \\
&= [\begin{pmatrix} \boldsymbol{X}_1' & \cdots & \boldsymbol{X}_N' \end{pmatrix} \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix} - T \begin{pmatrix} \bar{\boldsymbol{x}}_1 & \cdots & \bar{\boldsymbol{x}}_N \end{pmatrix} \begin{pmatrix} \bar{\boldsymbol{x}}_1' \\ \vdots \\ \bar{\boldsymbol{x}}_N' \end{pmatrix}]^{-1} (\begin{pmatrix} \boldsymbol{X}_1' & \cdots & \boldsymbol{X}_N' \end{pmatrix} \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} - T \begin{pmatrix} \bar{\boldsymbol{x}}_1 & \cdots & \bar{\boldsymbol{x}}_N \end{pmatrix} \begin{pmatrix} \bar{y}_1 \\ \vdots \\ \bar{y}_N \end{pmatrix}) \\
&= [\boldsymbol{X}'\boldsymbol{X} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{X}}]^{-1}(\boldsymbol{X}'\boldsymbol{y} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{y}}) && \text{Level 3}
\end{aligned}
$$

It is because

$$
\begin{aligned}
(\boldsymbol{QX}_i)'\boldsymbol{QX}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i') \\
&= (\boldsymbol{X}_i' - \bar{\boldsymbol{x}}_i'' \boldsymbol{e}')(\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i') \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \boldsymbol{X}_i'\boldsymbol{e}\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{X}_i + \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{e}\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \boldsymbol{X}_i'\boldsymbol{e}\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{X}_i + \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - (\boldsymbol{e}'\boldsymbol{X}_i)'\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{X}_i + \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - (\sum_{t=1}^{T} \boldsymbol{x}_{it}')'\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i \sum_{t=1}^{T} \boldsymbol{x}_{it}' + \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - (\sum_{t=1}^{T} \boldsymbol{x}_{it}/T)T\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i T \sum_{t=1}^{T} \boldsymbol{x}_{it}'/T + \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i' + \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \bar{\boldsymbol{x}}_i T\bar{\boldsymbol{x}}_i'
\end{aligned}
$$

$$
\begin{aligned}
(\boldsymbol{QX}_i)'\boldsymbol{Qy}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i) \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - \boldsymbol{X}_i'\boldsymbol{e}\bar{y}_i - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{y}_i + \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{e}\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - (\boldsymbol{e}'\boldsymbol{X}_i)'\bar{y}_i - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{y}_i + \bar{\boldsymbol{x}}_i T\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - (\sum_{t=1}^{T} \boldsymbol{x}_{it}')'\bar{y}_i - \bar{\boldsymbol{x}}_i \sum_{t=1}^{T} y_{it} + \bar{\boldsymbol{x}}_i T\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - (\sum_{t=1}^{T} \boldsymbol{x}_{it}/T)T\bar{y}_i - \bar{\boldsymbol{x}}_i T \sum_{t=1}^{T} y_{it}/T + \bar{\boldsymbol{x}}_i T\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - \bar{\boldsymbol{x}}_i T\bar{y}_i - \bar{\boldsymbol{x}}_i T\bar{y}_i + \bar{\boldsymbol{x}}_i T\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - \bar{\boldsymbol{x}}_i T\bar{y}_i
\end{aligned}
$$

### 1.3.4 The necessary condition for consistency and unbiasedness

The necessary condition for FE estimator (OLS estimator of the demean transformed model) to be consistent is $\mathbb{E}((\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) = \mathbf{0}$.

$$\begin{aligned}
\mathbb{E}((\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) &= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) \\
&= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) && \text{as } \boldsymbol{Q} \text{ is idempotent and symmetric} \\
&= \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)) \\
&= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\mathbf{0}}) && \text{because of strict exogeneity} \\
&= \mathbf{0}
\end{aligned}$$

Thus, FE estimator satisfies the necessary condition for consistency given strict exogeneity assumption. Indeed, strict exogeneity is stronger than what is required. To see this, first note that for any $t$,

$$\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \mathbb{E}(\varepsilon_{it}|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT}) = \mathbf{0} \implies \mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \mathbf{0} \qquad \text{for all } s$$

It is because for any $t$ and $s$,

$$\begin{aligned}
\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) &= \mathbb{E}(\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT})) \\
&= \mathbb{E}(\boldsymbol{x}_{is}\underbrace{\mathbb{E}(\varepsilon_{it}|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT})}_{0}) \\
&= \mathbf{0}
\end{aligned}$$

The necessary condition for FE estimator to be consistent can also be written as $\mathbb{E}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\varepsilon_{it} - \bar{\varepsilon}_i)) = \mathbf{0}$.

$$\mathbb{E}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\varepsilon_{it} - \bar{\varepsilon}_i)) = \mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{it}) - \mathbb{E}(\boldsymbol{x}_{it}\bar{\varepsilon}_i) - \mathbb{E}(\bar{\boldsymbol{x}}_i\varepsilon_{it}) + \mathbb{E}(\bar{\boldsymbol{x}}_i\bar{\varepsilon}_i) = \mathbf{0}$$

It is because $\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \mathbf{0}$ for any $t$ and $s$ implies

$$\begin{aligned}
\mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{it}) &= \mathbf{0} \\
\mathbb{E}(\boldsymbol{x}_{it}\bar{\varepsilon}_i) &= \mathbb{E}(\boldsymbol{x}_{it}T^{-1}\sum_{s=1}^{T}\varepsilon_{is}) = T^{-1}\sum_{s=1}^{T}\underbrace{\mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{is})}_{\mathbf{0}} = \mathbf{0} \\
\mathbb{E}(\bar{\boldsymbol{x}}_i\varepsilon_{it}) &= \mathbb{E}(T^{-1}\sum_{s=1}^{T}\boldsymbol{x}_{is}\varepsilon_{it}) = T^{-1}\sum_{s=1}^{T}\underbrace{\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it})}_{\mathbf{0}} = \mathbf{0} \\
\mathbb{E}(\bar{\boldsymbol{x}}_i\bar{\varepsilon}_i) &= \mathbb{E}(T^{-1}\sum_{s=1}^{T}\boldsymbol{x}_{is}T^{-1}\sum_{t=1}^{T}\varepsilon_{it}) = T^{-2}\sum_{s=1}^{T}\sum_{t=1}^{T}\underbrace{\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it})}_{\mathbf{0}} = \mathbf{0}
\end{aligned}$$

Thus, the weaker assumption $\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \mathbf{0}$ for any $t$ and $s$ is sufficient for $\mathbb{E}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\varepsilon_{it} - \bar{\varepsilon}_i)) = \mathbf{0}$

The necessary condition for FE estimator to be unbiased is $\mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{Q}\boldsymbol{X}_i) = \mathbf{0}$.

$$\begin{aligned}
\mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{Q}\boldsymbol{X}_i) &= \boldsymbol{Q}\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\mathbf{0}} && \text{as } \boldsymbol{Q} \text{ is constant and strict exogeneity} \\
&= \mathbf{0}
\end{aligned}$$

### 1.3.5 Conditional Variance of $\widehat{\boldsymbol{\beta}}^{ols}_{within}$

Given independence of $i$,

$$\begin{aligned}
Var(\widehat{\boldsymbol{\beta}}^{ols}_{within}|\boldsymbol{X}_i) &= Var([\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i) \\
&= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}Var(\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i)[\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1'} \\
&= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}
\end{aligned}$$

It is because

$$\begin{aligned}
Var(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i) &= \sum_{i=1}^{N} Var(\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i) \\
&= \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i)(\boldsymbol{X}_i'\boldsymbol{Q}')' \\
&= \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}''\boldsymbol{X}_i'' \\
&= \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}\boldsymbol{X}_i
\end{aligned}$$

### 1.3.6 $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2\boldsymbol{I}_T$

If $\varepsilon_{it}$ is homoskedasticity and serially uncorrelated across $t$ i.e., $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2\boldsymbol{I}_T$ (further assume independence of $i$ and strict exogeneity), we have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma_\varepsilon^2\boldsymbol{I}_T]$.

$$Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{Q}Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}' = \boldsymbol{Q}\sigma_\varepsilon^2\boldsymbol{I}_T\boldsymbol{Q}' = \sigma_\varepsilon^2\boldsymbol{Q}\boldsymbol{Q}' = \sigma_\varepsilon^2\boldsymbol{Q} = \sigma_\varepsilon^2(\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}') = \sigma_\varepsilon^2 \begin{pmatrix} 1-\frac{1}{T} & -\frac{1}{T} & \cdots & -\frac{1}{T} \\ -\frac{1}{T} & 1-\frac{1}{T} & \cdots & -\frac{1}{T} \\ \vdots & \vdots & \vdots & \vdots \\ -\frac{1}{T} & -\frac{1}{T} & \cdots & 1-\frac{1}{T} \end{pmatrix}.$$

Thus, $\boldsymbol{Q}\boldsymbol{\varepsilon}_i$ is homoskedasticity but negatively serially correlated. For any $t$,

$$\begin{aligned}
Var(\varepsilon_{it} - \bar{\varepsilon}_i) = \sigma_\varepsilon^2(1 - \frac{1}{T}) \iff \sigma_\varepsilon^2 &= \frac{T}{T-1}Var(\varepsilon_{it} - \bar{\varepsilon}_i) \\
\hat{\sigma}_\varepsilon^2 &= \frac{T}{T-1}\widehat{Var}(\widehat{\varepsilon_{it} - \bar{\varepsilon}_i}) \\
&= \frac{T}{T-1}\frac{\sum_{i=1}^{N}\sum_{t=1}^{T}(y_{it} - \bar{y}_i - (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\widehat{\boldsymbol{\beta}}_{within}^{ols})^2}{NT - (K+N)} \\
&= \frac{T}{T-1}\frac{\sum_{i=1}^{N}\sum_{t=1}^{T}(y_{it} - \boldsymbol{x}_{it}'\widehat{\boldsymbol{\beta}}_{within}^{ols} - \overbrace{(\bar{y}_i - \bar{\boldsymbol{x}}_i'\widehat{\boldsymbol{\beta}}_{within}^{ols})}^{\widehat{\alpha}_i})^2}{\underbrace{NT - (K+N)}_{N(T-1)-K}} \qquad \frac{T}{T-1} \approx 1 \text{ if } T \text{ is large.}
\end{aligned}$$

$$\begin{aligned}
Var(\widehat{\boldsymbol{\beta}}_{within}^{ols}|\boldsymbol{X}_i) &= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\sigma_\varepsilon^2\underbrace{\boldsymbol{Q}\boldsymbol{Q}}_{\boldsymbol{Q}}\boldsymbol{X}_i[\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= \sigma_\varepsilon^2[\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= \sigma_\varepsilon^2\boldsymbol{I}_T[\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= \sigma_\varepsilon^2[\sum_{i=1}^{N}(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} && \text{Level 2} \\
&= \sigma_\varepsilon^2[\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1} && \text{Level 1}
\end{aligned}$$

### 1.3.7 $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{\Omega}_i$

We have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim inid\ [\mathbf{0}, \boldsymbol{\Omega}_i]$.

$$\begin{aligned}
Var(\widehat{\boldsymbol{\beta}}^{ols}_{within}|\boldsymbol{X}_i) &= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\mathbf{0})(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\mathbf{0})'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[\boldsymbol{Q}\boldsymbol{\varepsilon}_i(\boldsymbol{Q}\boldsymbol{\varepsilon}_i)'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= [\sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\mathbb{E}[\boldsymbol{Q}\boldsymbol{\varepsilon}_i(\boldsymbol{Q}\boldsymbol{\varepsilon}_i)'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \\
&= [\sum_{i=1}^{N}\sum_{t=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1} \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)\mathbb{E}[\dot{\varepsilon}_{it}\dot{\varepsilon}_{is}|\boldsymbol{X}_i](\boldsymbol{x}_{is} - \bar{\boldsymbol{x}}_i)'[\sum_{i=1}^{N}\sum_{t=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1}
\end{aligned}$$

It is because

$$\begin{aligned}
\sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\mathbb{E}[\boldsymbol{Q}\boldsymbol{\varepsilon}_i(\boldsymbol{Q}\boldsymbol{\varepsilon}_i)'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i &= \sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\mathbb{E}[\dot{\boldsymbol{\varepsilon}}_i\dot{\boldsymbol{\varepsilon}}_i'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i \\
&= \sum_{i=1}^{N} \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)' \end{pmatrix}' \begin{pmatrix} \mathbb{E}[\dot{\varepsilon}_{i1}^2|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{i1}\dot{\varepsilon}_{iT}|\boldsymbol{X}_i] \\ \vdots & \ddots & \vdots \\ \mathbb{E}[\dot{\varepsilon}_{iT}\dot{\varepsilon}_{i1}|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{iT}^2|\boldsymbol{X}_i] \end{pmatrix} \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)' \end{pmatrix} \\
&= \sum_{i=1}^{N} \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i) & (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i) \end{pmatrix} \begin{pmatrix} \mathbb{E}[\dot{\varepsilon}_{i1}^2|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{i1}\dot{\varepsilon}_{iT}|\boldsymbol{X}_i] \\ \vdots & \ddots & \vdots \\ \mathbb{E}[\dot{\varepsilon}_{iT}\dot{\varepsilon}_{i1}|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{iT}^2|\boldsymbol{X}_i] \end{pmatrix} \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)' \end{pmatrix} \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)\mathbb{E}[\dot{\varepsilon}_{it}\dot{\varepsilon}_{is}|\boldsymbol{X}_i](\boldsymbol{x}_{is} - \bar{\boldsymbol{x}}_i)'
\end{aligned}$$

Finite sample adjustment can also be added. In Stata, $\frac{N}{N-1}\frac{T-1}{T-(K-1)}$ is multiplied.

### 1.3.8 GLS estimator of the demean transformed model if $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2\boldsymbol{I}_T$

$\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\mathbf{0}, \sigma_\varepsilon^2\boldsymbol{I}_T]$ implies $\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\mathbf{0}, \sigma_\varepsilon^2\boldsymbol{Q}]$, we want to find a GLS transformer $\boldsymbol{T}_{GLS}$ such that

$$\begin{aligned}
Var(\boldsymbol{T}_{GLS}\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{T}_{GLS}' &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\sigma_\varepsilon^2\boldsymbol{Q}\boldsymbol{T}_{GLS}' &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2}\boldsymbol{Q}^{1/2}\boldsymbol{T}_{GLS}' &= \boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2}\boldsymbol{Q}'^{1/2}\boldsymbol{T}_{GLS}' &= \boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2}(\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2})' &= \boldsymbol{I}_T
\end{aligned}$$

So, $\boldsymbol{T}_{GLS} = \boldsymbol{Q}^{-1/2}$

$$\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i = \boldsymbol{Q}^{-1/2}(\boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}\boldsymbol{\varepsilon}_i) = \boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{\varepsilon}_i$$

Thus, we have $Var(\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{Q}^{-1/2}Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}'^{-1/2} = \boldsymbol{Q}^{-1/2}\sigma_\varepsilon^2\boldsymbol{Q}\boldsymbol{Q}^{-1/2} = \sigma_\varepsilon^2\boldsymbol{Q}^{-1/2}\boldsymbol{Q}^{1/2}\boldsymbol{Q}^{1/2}\boldsymbol{Q}^{-1/2} = \sigma_\varepsilon^2\boldsymbol{I}_T$.

By Gauss-Markov Theorem, GLS estimator is efficient.

$$\begin{aligned}
\widehat{\boldsymbol{\beta}}^{gls}_{within} &= [\sum_{i=1}^{N}(\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i \\
&= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}'^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}'^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i \\
&= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i \\
&= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{Q}\boldsymbol{y}_i \\
&= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i = \widehat{\boldsymbol{\beta}}^{ols}_{within} && \text{So, FE estimator is also efficient}
\end{aligned}$$

For generalized inverse, $\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{Q} = \boldsymbol{Q}$. As $\boldsymbol{Q}$ is idempotent and symmetry, $\boldsymbol{Q} = \boldsymbol{Q}\boldsymbol{Q}' = \boldsymbol{Q}'\boldsymbol{Q}$. Therefore, $\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{Q} = \boldsymbol{Q}'\boldsymbol{Q}$.

## 1.4 First-Difference Estimator

### 1.4.1 First-difference operator

$$\boldsymbol{\Delta} = \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix}$$

$$\begin{aligned}
\boldsymbol{\Delta}\boldsymbol{\Delta}' &= \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix}' \\
&= \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} -1 & 0 & 0 & \cdots & 0 & 0 \\ 1 & -1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & -1 \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{pmatrix} \\
&= \begin{pmatrix} 2 & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2 & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2 & -1 \\ 0 & 0 & 0 & \cdots & -1 & 2 \end{pmatrix}
\end{aligned}$$

### 1.4.2 First difference transformed model

$$\begin{aligned}
\boldsymbol{\Delta}\boldsymbol{y}_i &= \boldsymbol{\Delta}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i) \\
&= \boldsymbol{\Delta}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{\Delta}\boldsymbol{e}\alpha_i + \boldsymbol{\Delta}\boldsymbol{\varepsilon}_i \\
&= \boldsymbol{\Delta}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{0}\alpha_i + \boldsymbol{\Delta}\boldsymbol{\varepsilon}_i \\
&= \boldsymbol{\Delta}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{\Delta}\boldsymbol{\varepsilon}_i && \text{Level 2}
\end{aligned}$$

It is because

$$\boldsymbol{\Delta e} = \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \\ \vdots \\ \vdots \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ \vdots \\ 0 \end{pmatrix} = \mathbf{0}$$

It can be written as

$$\begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} y_{i1} \\ y_{i2} \\ y_{i3} \\ \vdots \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} \boldsymbol{x}'_{i1} \\ \boldsymbol{x}'_{i2} \\ \boldsymbol{x}'_{i3} \\ \vdots \\ \vdots \\ \boldsymbol{x}'_{iT} \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_{i1} \\ \varepsilon_{i2} \\ \varepsilon_{i3} \\ \vdots \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$

$$\begin{pmatrix} y_{i2} - y_{i1} \\ y_{i3} - y_{i2} \\ y_{i4} - y_{i3} \\ \vdots \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}'_{i2} - \boldsymbol{x}'_{i1} \\ \boldsymbol{x}'_{i3} - \boldsymbol{x}'_{i2} \\ \boldsymbol{x}'_{i4} - \boldsymbol{x}'_{i3} \\ \vdots \\ \vdots \\ \boldsymbol{x}'_{iT} - \boldsymbol{x}'_{i,T-1} \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \varepsilon_{i2} - \varepsilon_{i1} \\ \varepsilon_{i3} - \varepsilon_{i2} \\ \varepsilon_{i4} - \varepsilon_{i3} \\ \vdots \\ \vdots \\ \varepsilon_{iT} - \varepsilon_{i,T-1} \end{pmatrix}$$

$$\begin{pmatrix} y_{i2} - y_{i1} \\ y_{i3} - y_{i2} \\ y_{i4} - y_{i3} \\ \vdots \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix} = \begin{pmatrix} (\boldsymbol{x}_{i2} - \boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4} - \boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1})' \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \varepsilon_{i2} - \varepsilon_{i1} \\ \varepsilon_{i3} - \varepsilon_{i2} \\ \varepsilon_{i4} - \varepsilon_{i3} \\ \vdots \\ \vdots \\ \varepsilon_{iT} - \varepsilon_{i,T-1} \end{pmatrix}$$

$$y_{it} - y_{i,t-1} = (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})'\boldsymbol{\beta} + (\varepsilon_{it} - \varepsilon_{i,t-1}) \qquad \text{Level 1}$$

### 1.4.3 OLS estimator of the first difference transformed model

$$\begin{aligned} \widehat{\boldsymbol{\beta}}_{fd}^{ols} &= [\sum_{i=1}^{N} (\boldsymbol{\Delta X}_i)' \boldsymbol{\Delta X}_i]^{-1} \sum_{i=1}^{N} (\boldsymbol{\Delta X}_i)' \boldsymbol{\Delta y}_i && \text{Level 2} \\ &= [\sum_{i=1}^{N} \sum_{t=2}^{T} (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})(\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})']^{-1} \sum_{i=1}^{N} \sum_{t=2}^{T} (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})(y_{it} - y_{i,t-1}) && \text{Level 1} \end{aligned}$$

It is because

$$
\begin{aligned}
(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i &= \begin{pmatrix} (\boldsymbol{x}_{i2}-\boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3}-\boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4}-\boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT}-\boldsymbol{x}_{i,T-1})' \end{pmatrix}' \begin{pmatrix} (\boldsymbol{x}_{i2}-\boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3}-\boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4}-\boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT}-\boldsymbol{x}_{i,T-1})' \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{x}_{i2}-\boldsymbol{x}_{i1}) & (\boldsymbol{x}_{i3}-\boldsymbol{x}_{i2}) & (\boldsymbol{x}_{i4}-\boldsymbol{x}_{i3}) & \cdots & \cdots & (\boldsymbol{x}_{iT}-\boldsymbol{x}_{i,T-1}) \end{pmatrix} \begin{pmatrix} (\boldsymbol{x}_{i2}-\boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3}-\boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4}-\boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT}-\boldsymbol{x}_{i,T-1})' \end{pmatrix} \\
&= \sum_{t=2}^{T}(\boldsymbol{x}_{it}-\boldsymbol{x}_{i,t-1})(\boldsymbol{x}_{it}-\boldsymbol{x}_{i,t-1})'
\end{aligned}
$$

$$
\begin{aligned}
(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta y}_i &= \begin{pmatrix} (\boldsymbol{x}_{i2}-\boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3}-\boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4}-\boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT}-\boldsymbol{x}_{i,T-1})' \end{pmatrix}' \begin{pmatrix} y_{i2}-y_{i1} \\ y_{i3}-y_{i2} \\ y_{i4}-y_{i3} \\ \vdots \\ \vdots \\ y_{iT}-y_{i,T-1} \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{x}_{i2}-\boldsymbol{x}_{i1}) & (\boldsymbol{x}_{i3}-\boldsymbol{x}_{i2}) & (\boldsymbol{x}_{i4}-\boldsymbol{x}_{i3}) & \cdots & \cdots & (\boldsymbol{x}_{iT}-\boldsymbol{x}_{i,T-1}) \end{pmatrix} \begin{pmatrix} y_{i2}-y_{i1} \\ y_{i3}-y_{i2} \\ y_{i4}-y_{i3} \\ \vdots \\ \vdots \\ y_{iT}-y_{i,T-1} \end{pmatrix} \\
&= \sum_{t=2}^{T}(\boldsymbol{x}_{it}-\boldsymbol{x}_{i,t-1})(y_{it}-y_{i,t-1})
\end{aligned}
$$

### 1.4.4 The necessary condition for consistency and unbiasedness

The necessary condition for FD estimator (OLS estimator of the FD transformed model) to be consistent is $\mathbb{E}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta\varepsilon}_i) = \mathbf{0}$

$$
\begin{aligned}
\mathbb{E}((\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta\varepsilon}_i) &= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{\Delta}'\boldsymbol{\Delta\varepsilon}_i) \\
&= \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{\Delta\Delta}'\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)) \\
&= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{\Delta\Delta}'\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\mathbf{0}}) && \text{because of strict exogeneity} \\
&= \mathbf{0}
\end{aligned}
$$

Thus, FD estimator satisfies the necessary condition for consistency given strict exogeneity assumption. Indeed, strict exogeneity is stronger than what is required. To see this, first note that for any $t$

$$\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \mathbb{E}(\varepsilon_{it}|\boldsymbol{x}_{i1},\cdots,\boldsymbol{x}_{iT}) = 0 \implies \mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \mathbf{0} \qquad \text{for all } s$$

The necessary condition for FD estimator to be consistent can also be written as $\mathbb{E}((\boldsymbol{x}_{it}-\boldsymbol{x}_{i,t-1})(\varepsilon_{it}-\varepsilon_{i,t-1})) = \mathbf{0}$

$$\mathbb{E}((\boldsymbol{x}_{it}-\boldsymbol{x}_{i,t-1})(\varepsilon_{it}-\varepsilon_{i,t-1})) = \mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{it}) - \mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{i,t-1}) - \mathbb{E}(\boldsymbol{x}_{i,t-1}\varepsilon_{it}) + \mathbb{E}(\boldsymbol{x}_{i,t-1}\varepsilon_{i,t-1}) = \mathbf{0}$$

It is because $\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \mathbf{0}$ for any $t$ and $s$ implies

$$\mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{it}) = \mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{i,t-1}) = \mathbb{E}(\boldsymbol{x}_{i,t-1}\varepsilon_{it}) = \mathbb{E}(\boldsymbol{x}_{i,t-1}\varepsilon_{i,t-1}) = \mathbf{0}$$

Thus, the weaker assumption $\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \mathbf{0}$ for any $t$ and $s$ is sufficient for $\mathbb{E}((\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})(\varepsilon_{it} - \varepsilon_{i,t-1})) = \mathbf{0}$

The necessary condition for FD estimator to be unbiased is $\mathbb{E}(\boldsymbol{\Delta\varepsilon}_i|\boldsymbol{\Delta X}_i) = \mathbf{0}$

$$\begin{aligned}
\mathbb{E}(\boldsymbol{\Delta\varepsilon}_i|\boldsymbol{\Delta X}_i) &= \boldsymbol{\Delta}\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\mathbf{0}} && \text{as } \boldsymbol{\Delta} \text{ is constant and strict exogeneity} \\
&= \mathbf{0}
\end{aligned}$$

### 1.4.5 Conditional Variance of $\widehat{\boldsymbol{\beta}}_{fd}^{ols}$

$$\begin{aligned}
Var(\widehat{\boldsymbol{\beta}}_{fd}^{ols}|\boldsymbol{X}_i) &= Var([\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta y}_i|\boldsymbol{X}_i) \\
&= [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}Var(\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta y}_i|\boldsymbol{X}_i)[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1'} \\
&= [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'Var(\boldsymbol{\Delta\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}
\end{aligned}$$

### 1.4.6 $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2\boldsymbol{I}_T$

If $\varepsilon_{it}$ is homoskedasticity and serially uncorrelated across $t$ i.e., $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2\boldsymbol{I}_T$ (further assume independence of $i$ and strict exogeneity), we have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\mathbf{0}, \sigma_\varepsilon^2\boldsymbol{I}_T]$.

$Var(\boldsymbol{\Delta\varepsilon_i}|\boldsymbol{X}_i) = \boldsymbol{\Delta}Var(\boldsymbol{\varepsilon}|\boldsymbol{X}_i)\boldsymbol{\Delta'} = \boldsymbol{\Delta}\sigma_\varepsilon^2\boldsymbol{I}_T\boldsymbol{\Delta'} = \sigma_\varepsilon^2\boldsymbol{\Delta\Delta'} = \sigma_\varepsilon^2\begin{pmatrix} 2 & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2 & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2 & -1 \\ 0 & 0 & 0 & \cdots & -1 & 2 \end{pmatrix}$ Thus, $\boldsymbol{\Delta\varepsilon}_i$ is homoskedasticity but not serially uncorrelated e.g. $Cov(\varepsilon_{it}-\varepsilon_{i,t-1}, \varepsilon_{i,t-1}-\varepsilon_{i,t-2}|\boldsymbol{X}_i) = -\sigma_\varepsilon^2 < 0$. Therefore, we cannot apply Gauss-Markov Theorem.

$$\begin{aligned}
Var(\widehat{\boldsymbol{\beta}}_{fd}^{ols}|\boldsymbol{X}_i) &= [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\sigma_\varepsilon^2\boldsymbol{\Delta\Delta'\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1} \\
&= \sigma_\varepsilon^2[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{\Delta'\Delta\Delta'\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}
\end{aligned}$$

### 1.4.7 $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{\Omega}_i$

We have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim inid\ [\mathbf{0}, \boldsymbol{\Omega}_i]$,

$Var(\boldsymbol{\Delta\varepsilon_i}|\boldsymbol{X}_i) = \boldsymbol{\Delta}Var(\boldsymbol{\varepsilon}|\boldsymbol{X}_i)\boldsymbol{\Delta'} = \boldsymbol{\Delta}\mathbb{E}[(\boldsymbol{\varepsilon}_i - \mathbb{E}[\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i])(\boldsymbol{\varepsilon}_i - \mathbb{E}[\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i])'|\boldsymbol{X}_i]\boldsymbol{\Delta'} = \boldsymbol{\Delta}\mathbb{E}[(\boldsymbol{\varepsilon}_i - \mathbf{0})(\boldsymbol{\varepsilon}_i - \mathbf{0})'|\boldsymbol{X}_i]\boldsymbol{\Delta'} = \boldsymbol{\Delta}\mathbb{E}[\boldsymbol{\varepsilon}_i\boldsymbol{\varepsilon}_i'|\boldsymbol{X}_i]\boldsymbol{\Delta'} = \mathbb{E}[\boldsymbol{\Delta\varepsilon}_i\boldsymbol{\varepsilon}_i'\boldsymbol{\Delta'}|\boldsymbol{X}_i] = \mathbb{E}[\boldsymbol{\Delta\varepsilon}_i(\boldsymbol{\Delta\varepsilon}_i)'|\boldsymbol{X}_i]$

$$Var(\widehat{\boldsymbol{\beta}}_{fd}^{ols}|\boldsymbol{X}_i) = [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'E[\boldsymbol{\Delta\varepsilon}_i(\boldsymbol{\Delta\varepsilon}_i)'|\boldsymbol{X}_i]\boldsymbol{\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}$$

If $\varepsilon_{it}$ follows random walk process i.e., $\varepsilon_{it} = \varepsilon_{i,t-1} + v_{it}$ where $v_{it}$ follows white noise process, $\varepsilon_{it} - \varepsilon_{i,t-1} = v_{it}$ follows white noise process. Thus, $\varepsilon_{it} - \varepsilon_{i,t-1}$ is homoskedasticity and serially uncorrelated as they are the properties of white noise process. As a result, FD estimator is efficient in this case by applying Gauss-Markov Theorem.

## 1.5 Least-Squares Dummy Variable Estimator

$$\boldsymbol{y} = (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} = \begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}\end{pmatrix}\begin{pmatrix}\boldsymbol{\alpha}\\ \boldsymbol{\beta}\end{pmatrix} + \boldsymbol{\varepsilon} \qquad \text{Level 3}$$

$$\begin{aligned}
\begin{pmatrix}\widehat{\boldsymbol{\alpha}}_{dv}^{ols}\\ \widehat{\boldsymbol{\beta}}_{dv}^{ols}\end{pmatrix} &= [\begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}\end{pmatrix}'\begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}\end{pmatrix}]^{-1}\begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}\end{pmatrix}'\boldsymbol{y}\\
&= \begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e})'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & (\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{X}\\ \boldsymbol{X}'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}'\boldsymbol{X}\end{pmatrix}^{-1}\begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{y}\\ \boldsymbol{X}'\boldsymbol{y}\end{pmatrix}\\
&= \begin{pmatrix}T\boldsymbol{I}_N & T\bar{\boldsymbol{X}}\\ T\bar{\boldsymbol{X}}' & \boldsymbol{X}'\boldsymbol{X}\end{pmatrix}^{-1}\begin{pmatrix}T\bar{\boldsymbol{y}}\\ \boldsymbol{X}'\boldsymbol{y}\end{pmatrix}\\
\widehat{\boldsymbol{\beta}}_{dv}^{ols} &= [\boldsymbol{X}'\boldsymbol{X} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{X}}]^{-1}(\boldsymbol{X}'\boldsymbol{y} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{y}}) = \widehat{\boldsymbol{\beta}}_{within}^{ols}
\end{aligned}$$

It is because

$$\begin{aligned}
\begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}\end{pmatrix}'\begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}\end{pmatrix} &= \begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e})'\\ \boldsymbol{X}'\end{pmatrix}\begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}\end{pmatrix}\\
&= \begin{pmatrix}(\boldsymbol{I}_N \otimes \boldsymbol{e})'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & (\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{X}\\ \boldsymbol{X}'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}'\boldsymbol{X}\end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
(\boldsymbol{I}_N \otimes \boldsymbol{e})'(\boldsymbol{I}_N \otimes \boldsymbol{e}) &= \begin{pmatrix}\boldsymbol{e} & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{e}\end{pmatrix}'\begin{pmatrix}\boldsymbol{e} & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{e}\end{pmatrix}\\
&= \begin{pmatrix}\boldsymbol{e}' & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{e}'\end{pmatrix}\begin{pmatrix}\boldsymbol{e} & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{e}\end{pmatrix}\\
&= \begin{pmatrix}\boldsymbol{e}'\boldsymbol{e} & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{e}'\boldsymbol{e}\end{pmatrix}\\
&= \begin{pmatrix}T & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & T\end{pmatrix}\\
&= T\boldsymbol{I}_N
\end{aligned}$$

$$\begin{aligned}
(\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{X} &= \begin{pmatrix}\boldsymbol{e}' & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{e}'\end{pmatrix}\begin{pmatrix}\boldsymbol{X}_1\\ \vdots\\ \boldsymbol{X}_N\end{pmatrix}\\
&= \begin{pmatrix}\boldsymbol{e}'\boldsymbol{X}_1\\ \vdots\\ \boldsymbol{e}'\boldsymbol{X}_N\end{pmatrix}\\
&= \begin{pmatrix}\sum_{t=1}^T \boldsymbol{x}_{1t}'\\ \vdots\\ \sum_{t=1}^T \boldsymbol{x}_{Nt}'\end{pmatrix}\\
&= \begin{pmatrix}T\sum_{t=1}^T \boldsymbol{x}_{1t}'/T\\ \vdots\\ T\sum_{t=1}^T \boldsymbol{x}_{Nt}'/T\end{pmatrix}\\
&= \begin{pmatrix}T\bar{\boldsymbol{x}}_1'\\ \vdots\\ T\bar{\boldsymbol{x}}_N'\end{pmatrix}\\
&= T\bar{\boldsymbol{X}}
\end{aligned}$$

$$\left((\boldsymbol{I}_N \otimes \boldsymbol{e}) \quad \boldsymbol{X}\right)' \boldsymbol{y} = \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})' \\ \boldsymbol{X}' \end{pmatrix} \boldsymbol{y} = \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{y} \\ \boldsymbol{X}'\boldsymbol{y} \end{pmatrix}$$

Another way to show the equivalence of within estimator and dummy variable estimator by using Frisch-Waugh-Lovell Theorem,

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon}$$
$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{E}\boldsymbol{\alpha} + \boldsymbol{\varepsilon}$$

$$\boldsymbol{X} = \boldsymbol{E}\boldsymbol{\alpha}_{XE} + \boldsymbol{\varepsilon}_{XE}$$
$$\boldsymbol{y} = \boldsymbol{E}\boldsymbol{\alpha}_{yE} + \boldsymbol{\varepsilon}_{yE}$$

$$\begin{aligned}
\widehat{\boldsymbol{\alpha}}_{yE} &= (\boldsymbol{E}'\boldsymbol{E})^{-1}\boldsymbol{E}'\boldsymbol{y} \\
&= \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}' \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix})^{-1} \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}' \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} \\
&= ( \begin{pmatrix} \boldsymbol{e}' & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}' \end{pmatrix} \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix})^{-1} \begin{pmatrix} \boldsymbol{e}' & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}' \end{pmatrix} \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \boldsymbol{e}'\boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}'\boldsymbol{e} \end{pmatrix}^{-1} \begin{pmatrix} \boldsymbol{e}'\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{e}'\boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{e}'\boldsymbol{e})^{-1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & (\boldsymbol{e}'\boldsymbol{e})^{-1} \end{pmatrix} \begin{pmatrix} \boldsymbol{e}'\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{e}'\boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{e}'\boldsymbol{e})^{-1}\boldsymbol{e}'\boldsymbol{y}_1 \\ \vdots \\ (\boldsymbol{e}'\boldsymbol{e})^{-1}\boldsymbol{e}'\boldsymbol{y}_N \end{pmatrix} = \begin{pmatrix} T^{-1}\sum_{t=1}^{T} y_{1t} \\ \vdots \\ T^{-1}\sum_{t=1}^{T} y_{Nt} \end{pmatrix} = \begin{pmatrix} \bar{y}_1 \\ \vdots \\ \bar{y}_N \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
\widehat{\boldsymbol{\varepsilon}}_{yE} = \boldsymbol{y} - \boldsymbol{E}\widehat{\boldsymbol{\alpha}}_{yE} &= \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} - \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \begin{pmatrix} \bar{y}_1 \\ \vdots \\ \bar{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} - \begin{pmatrix} \boldsymbol{e}\bar{y}_1 \\ \vdots \\ \boldsymbol{e}\bar{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \boldsymbol{y}_1 - \boldsymbol{e}\bar{y}_1 \\ \vdots \\ \boldsymbol{y}_N - \boldsymbol{e}\bar{y}_N \end{pmatrix} = \begin{pmatrix} \boldsymbol{Q}\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{Q}\boldsymbol{y}_N \end{pmatrix} = \boldsymbol{Q}\boldsymbol{y}
\end{aligned}$$

Similarly,

$$\widehat{\boldsymbol{\varepsilon}}_{XE} = \boldsymbol{Q}\boldsymbol{X}$$

By Frisch-Waugh-Lovell Theorem,

$$\begin{aligned}
\widehat{\boldsymbol{\beta}}^{ols}_{dv} &= (\widehat{\boldsymbol{\varepsilon}}'_{XE}\widehat{\boldsymbol{\varepsilon}}_{XE})^{-1}\widehat{\boldsymbol{\varepsilon}}'_{XE}\widehat{\boldsymbol{\varepsilon}}_{yE} \\
&= [(\boldsymbol{Q}\boldsymbol{X})'\boldsymbol{Q}\boldsymbol{X}]^{-1}(\boldsymbol{Q}\boldsymbol{X})'\boldsymbol{Q}\boldsymbol{y} = \widehat{\boldsymbol{\beta}}^{ols}_{within}
\end{aligned}$$

If $N \to \infty$, the number of $\alpha_i$ estimated goes to infinity. If $T$ is fixed, the LSDV estimates are consistent for $\boldsymbol{\beta}$ (as FE estimates for $\boldsymbol{\beta}$ is consistent for fixed $T$ and $N \to \infty$) but inconsistent for $\boldsymbol{\alpha}$. (There is no incidental parameters problem as the estimates for $\boldsymbol{\beta}$ are not contaminated). If $T$ also $\to \infty$, then the LSDV estimates of $\boldsymbol{\alpha}$ are also consistent.

# 2 Random Effect Model

$$y_{it} = \boldsymbol{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \alpha_i + \begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$
$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i}$$

$$\begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} = \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{pmatrix} + \begin{pmatrix} \boldsymbol{\varepsilon}_1 \\ \vdots \\ \boldsymbol{\varepsilon}_N \end{pmatrix}$$
$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon}$$

## 2.1 Assumptions

### 2.1.1 Strong/Strict Exogeneity of Regressors

For all $t$,

$$E(\varepsilon_{it}|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT}) = 0$$

Equivalently,

$$E(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{0}$$

### 2.1.2 Covariance Structure

$$\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma_\varepsilon^2\boldsymbol{I}_T]$$
$$\alpha_i|\boldsymbol{X}_i \sim iid\ [0, \sigma_\alpha^2]$$
$$\boldsymbol{\varepsilon}_i \perp \alpha_i|\boldsymbol{X}_i$$

## 2.2 Moments of $\boldsymbol{u}_i|\boldsymbol{X}_i$

$$\begin{aligned}
\boldsymbol{\Omega} := Var(\boldsymbol{u}_i|\boldsymbol{X}_i) &= Var(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) && \text{because of } \boldsymbol{\varepsilon}_i \perp \alpha_i|\boldsymbol{X}_i \\
&= Var(\boldsymbol{e}\alpha_i|\boldsymbol{X}_i) + Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) \\
&= \boldsymbol{e}Var(\alpha_i|\boldsymbol{X}_i)\boldsymbol{e}' + Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) \\
&= \sigma_\alpha^2\boldsymbol{e}\boldsymbol{e}' + \sigma_\varepsilon^2\boldsymbol{I}_T \\
&= \begin{pmatrix} \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 \\ \vdots & \ddots & \vdots \\ \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 \end{pmatrix} + \begin{pmatrix} \sigma_\varepsilon^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_\varepsilon^2 \end{pmatrix} \\
&= \begin{pmatrix} \sigma_\alpha^2 + \sigma_\varepsilon^2 & \cdots & \sigma_\alpha^2 \\ \vdots & \ddots & \vdots \\ \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 + \sigma_\varepsilon^2 \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) &= \mathbb{E}(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) \\
&= \boldsymbol{e}\underbrace{\mathbb{E}(\alpha_i|\boldsymbol{X}_i)}_{0} + \underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\boldsymbol{0}} \\
&= \boldsymbol{0}
\end{aligned}$$

Note that $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = \mathbb{E}(\alpha_i|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT}) = 0$ called orthogonality assumption. $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies Cov(\alpha_i, \boldsymbol{X}_i) = \boldsymbol{0}$. It is because $Cov(\alpha_i, \boldsymbol{X}_i) = \mathbb{E}(\alpha_i\boldsymbol{X}_i) - \mathbb{E}(\alpha_i)\mathbb{E}(\boldsymbol{X}_i) = \mathbb{E}(\mathbb{E}(\alpha_i\boldsymbol{X}_i|\boldsymbol{X}_i)) - \mathbb{E}(\mathbb{E}(\alpha_i|\boldsymbol{X}_i))\mathbb{E}(\boldsymbol{X}_i) = \mathbb{E}(\mathbb{E}(\alpha_i|\boldsymbol{X}_i)\boldsymbol{X}_i) = \boldsymbol{0}$. There is no OVB i.e., $\boldsymbol{u}_i$ is not correlated with $\boldsymbol{X}_i$.

$\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0}$ means that the necessary condition for OLS estimator to be unbiased is satisfied. Moreover, $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \boldsymbol{0}$ which means that the necessary condition for OLS estimator to be consistent is also satisfied. However, $\boldsymbol{u}_i|\boldsymbol{X}_i$ is homoskedasticity but serially correlated. Thus, the necessary condition for OLS estimator to be efficient is not satisfied. As a result, it is not efficient.

As we know the covariance structure of $\boldsymbol{u}_i|\boldsymbol{X}_i$ due to the strong assumptions in random effect model, we can use GLS estimation, which yields efficient estimates.

## 2.3 Random Effect Estimator (GLS Estimator)

### 2.3.1 GLS transformed model

We want to find a $\boldsymbol{T}_{GLS}$ such that

$$\begin{aligned}
Var(\boldsymbol{T}_{GLS}\boldsymbol{u}_i|\boldsymbol{X}_i) &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}Var(\boldsymbol{u}_i|\boldsymbol{X}_i)\boldsymbol{T}_{GLS}' &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\boldsymbol{\Omega}\boldsymbol{T}_{GLS}' &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}^{1/2}\boldsymbol{T}_{GLS}' &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}'^{1/2}\boldsymbol{T}_{GLS}' &= \sigma_\varepsilon^2\boldsymbol{I}_T \\
\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2}(\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2})' &= \sigma_\varepsilon^2\boldsymbol{I}_T
\end{aligned}$$

So, $\boldsymbol{T}_{GLS} = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}$. Define $\psi^2 := \frac{\sigma_\varepsilon^2}{T\sigma_\alpha^2+\sigma_\varepsilon^2}$.

$$\begin{aligned}
\boldsymbol{\Omega} &= \sigma_\varepsilon^2\boldsymbol{I}_T + \sigma_\alpha^2\boldsymbol{e}\boldsymbol{e}' \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{\sigma_\alpha^2}{\sigma_\varepsilon^2}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{T\sigma_\alpha^2}{\sigma_\varepsilon^2}T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{T\sigma_\alpha^2 + \sigma_\varepsilon^2 - \sigma_\varepsilon^2}{\sigma_\varepsilon^2}T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + (\frac{T\sigma_\alpha^2 + \sigma_\varepsilon^2}{\sigma_\varepsilon^2} - 1)T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + (\frac{1}{\psi^2} - 1)T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{1}{\psi^2}T^{-1}\boldsymbol{e}\boldsymbol{e}' - T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' + \frac{1}{\psi^2}(T^{-1}\boldsymbol{e}\boldsymbol{e}' - \boldsymbol{I}_T + \boldsymbol{I}_T)) \\
&= \sigma_\varepsilon^2(\boldsymbol{Q} + \frac{1}{\psi^2}(\boldsymbol{I}_T - \boldsymbol{Q}))
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\Omega}^{-1} &= [\sigma_\varepsilon^2(\boldsymbol{Q} + \frac{1}{\psi^2}(\boldsymbol{I}_T - \boldsymbol{Q}))]^{-1} \\
&= \sigma_\varepsilon^{-2}(\boldsymbol{Q}^- + \psi^2(\boldsymbol{I}_T^{-1} - \boldsymbol{Q}^-)) \\
&= \sigma_\varepsilon^{-2}(\boldsymbol{Q} + \psi^2(\boldsymbol{I}_T - \boldsymbol{Q}))
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\Omega}^{-1/2} &= \sigma_\varepsilon^{-1}(\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q})) \\
\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2} &= (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))
\end{aligned}$$

$$\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{y}_i = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + (\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)) = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{u}_i) = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{X}_i\boldsymbol{\beta} + \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{u}_i$$

So, $Var(\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{u}_i|\boldsymbol{X}_i) = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}Var(\boldsymbol{u}_i|\boldsymbol{X}_i)\sigma_\varepsilon\boldsymbol{\Omega}^{'-1/2} = \sigma_\varepsilon^2\boldsymbol{\Omega}^{-1/2}\boldsymbol{\Omega}\boldsymbol{\Omega}^{-1/2} = \sigma_\varepsilon^2\boldsymbol{\Omega}^{-1/2}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}^{-1/2} = \sigma_\varepsilon^2\boldsymbol{I}_T$

$$(\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{y}_i = (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{X}_i\boldsymbol{\beta} + (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{e}\alpha_i + (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{\varepsilon}_i \qquad \text{Level 2}$$

It can also be written as

$$\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i) \qquad \text{Level 2}$$

where $\lambda = 1 - \psi = 1 - \frac{\sigma_\varepsilon}{\sqrt{T\sigma_\alpha^2+\sigma_\varepsilon^2}}$. It is because

$$\begin{aligned}
\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{y}_i = (\boldsymbol{Q}+\psi(\boldsymbol{I}_T-\boldsymbol{Q}))\boldsymbol{y}_i &= \boldsymbol{Q}\boldsymbol{y}_i + \psi(\boldsymbol{I}_T\boldsymbol{y}_i - \boldsymbol{Q}\boldsymbol{y}_i)\\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i + \psi(\boldsymbol{y}_i - \boldsymbol{y}_i + \boldsymbol{e}\bar{y}_i)\\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i + \psi\boldsymbol{e}\bar{y}_i\\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i(1-\psi)\\
&= \boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i
\end{aligned}$$

$$\begin{aligned}
\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{X}_i\boldsymbol{\beta} = (\boldsymbol{Q}+\psi(\boldsymbol{I}_T-\boldsymbol{Q}))\boldsymbol{X}_i\boldsymbol{\beta} &= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \psi(\boldsymbol{I}_T\boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta})\\
&= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + \psi(\boldsymbol{X}_i\boldsymbol{\beta} - (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta})\\
&= (\boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta}) + \psi(\boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta})\\
&= \boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta} + \psi\boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta}\\
&= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i' + \psi\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta}\\
&= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i'(1-\psi))\boldsymbol{\beta}\\
&= (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta}
\end{aligned}$$

$$\begin{aligned}
\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{e}\alpha_i = (\boldsymbol{Q}+\psi(\boldsymbol{I}_T-\boldsymbol{Q}))\boldsymbol{e}\alpha_i &= \boldsymbol{Q}\boldsymbol{e}\alpha_i + \psi(\boldsymbol{I}_T\boldsymbol{e}\alpha_i - \boldsymbol{Q}\boldsymbol{e}\alpha_i)\\
&= \boldsymbol{0}\alpha_i + \psi(\boldsymbol{e}\alpha_i - \boldsymbol{0}\alpha_i)\\
&= \psi\boldsymbol{e}\alpha_i\\
&= (1-\lambda)\boldsymbol{e}\alpha_i
\end{aligned}$$

Random effect estimator is the OLS estimator of the beta in the transformed model $\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)$.

Fixed effect / within estimator is the OLS estimator of the beta in the transformed model $\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)$.

Pooled OLS estimator is the OLS estimator of the beta in the original model $\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i$.

As $T \to \infty$, $\lambda \to 1$, $\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)$ converges to $\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)$ Thus, random effect estimator converges to fixed effect / within estimator as $T \to \infty$.

As $\sigma_\alpha^2 \to 0$, $\lambda \to 0$, $\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)$ converges to $\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i$ Thus, random effect estimator converges to pooled OLS estimator as $\sigma_\alpha^2 \to 0$.

$$\begin{aligned}
\begin{pmatrix} y_{i1}\\ \vdots \\ y_{iT}\end{pmatrix} - \lambda \begin{pmatrix} 1\\ \vdots \\ 1\end{pmatrix}\bar{y}_i &= (\begin{pmatrix} \boldsymbol{x}_{i1}'\\ \vdots \\ \boldsymbol{x}_{iT}'\end{pmatrix} - \lambda\begin{pmatrix} 1\\ \vdots \\ 1\end{pmatrix}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1-\lambda)\begin{pmatrix} 1\\ \vdots \\ 1\end{pmatrix}\alpha_i + (\begin{pmatrix} \varepsilon_{i1}\\ \vdots \\ \varepsilon_{iT}\end{pmatrix} - \lambda\begin{pmatrix} 1\\ \vdots \\ 1\end{pmatrix}\bar{\varepsilon}_i)\\
\begin{pmatrix} y_{i1} - \lambda\bar{y}_i\\ \vdots \\ y_{iT} - \lambda\bar{y}_i\end{pmatrix} &= \begin{pmatrix} \boldsymbol{x}_{i1}' - \lambda\bar{\boldsymbol{x}}_i'\\ \vdots \\ \boldsymbol{x}_{iT}' - \lambda\bar{\boldsymbol{x}}_i'\end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} (1-\lambda)\alpha_i\\ \vdots \\ (1-\lambda)\alpha_i\end{pmatrix} + \begin{pmatrix} \varepsilon_{i1} - \lambda\bar{\varepsilon}_i\\ \vdots \\ \varepsilon_{iT} - \lambda\bar{\varepsilon}_i\end{pmatrix}\\
\begin{pmatrix} y_{i1} - \lambda\bar{y}_i\\ \vdots \\ y_{iT} - \lambda\bar{y}_i\end{pmatrix} &= \begin{pmatrix} (\boldsymbol{x}_{i1} - \lambda\bar{\boldsymbol{x}}_i)'\\ \vdots \\ (\boldsymbol{x}_{iT} - \lambda\bar{\boldsymbol{x}}_i)'\end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} (1-\lambda)\alpha_i\\ \vdots \\ (1-\lambda)\alpha_i\end{pmatrix} + \begin{pmatrix} \varepsilon_{i1} - \lambda\bar{\varepsilon}_i\\ \vdots \\ \varepsilon_{iT} - \lambda\bar{\varepsilon}_i\end{pmatrix}\\
y_{it} - \lambda\bar{y}_i &= (\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + \underbrace{(1-\lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)}_{v_{it}} \qquad \text{Level 1}
\end{aligned}$$

### 2.3.2 OLS estimator of the GLS transformed model i.e., Random Effect / GLS estimator

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{re}^{ols} &= [\sum_{i=1}^{N}(\boldsymbol{X}_i - \lambda \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{X}_i - \lambda \boldsymbol{e}\bar{\boldsymbol{x}}_i')]^{-1}\sum_{i=1}^{N}(\boldsymbol{X}_i - \lambda \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{y}_i - \lambda \boldsymbol{e}\bar{y}_i) && \text{Level 2} \\
&= [\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)']^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)(y_{it} - \lambda\bar{y}_i) && \text{Level 1}
\end{aligned}
$$

If $\boldsymbol{x}_{it}$ is replaced by $\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}$ and $\bar{\boldsymbol{x}}_i$ is replaced by $\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}$,

$$
\begin{aligned}
(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}) &= \boldsymbol{x}_{it} - \bar{\boldsymbol{x}} - \lambda\bar{\boldsymbol{x}}_i + \lambda\bar{\boldsymbol{x}} \\
&= \boldsymbol{x}_{it} - \bar{\boldsymbol{x}} - (1-\psi)\bar{\boldsymbol{x}}_i + (1-\psi)\bar{\boldsymbol{x}} \\
&= \boldsymbol{x}_{it} - \bar{\boldsymbol{x}} - \bar{\boldsymbol{x}}_i + \psi\bar{\boldsymbol{x}}_i + \bar{\boldsymbol{x}} - \psi\bar{\boldsymbol{x}} \\
&= (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + \psi(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}) \\
\sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))' &= \sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + \psi(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + \psi(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \psi\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' + \\
&\quad \psi\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})'
\end{aligned}
$$

It is because

$$
\begin{aligned}
\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' &= \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' - \sum_{i=1}^{N}\sum_{t=1}^{T}\bar{\boldsymbol{x}}_i(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' - \sum_{i=1}^{N}T\bar{\boldsymbol{x}}_i(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' - \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \boldsymbol{0}
\end{aligned}
$$

Similarly, if $y_{it}$ is replaced by $y_{it} - \bar{y}$ and $\bar{y}_i$ is replaced by $\bar{y}_i - \bar{y}$

$$
\sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))((y_{it} - \bar{y}) - \lambda(\bar{x}_i - \bar{y})) = \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{y}_i - \bar{y})
$$

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{re}^{ols} = (&\overbrace{\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'}^{Within} + \psi^2\overbrace{\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})'}^{Between})^{-1} \\
&(\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{y}_i - \bar{y}))
\end{aligned}
$$

If $T \to \infty$, $\psi^2 \to 0$, $\hat{\boldsymbol{\beta}}_{re}^{ols} \to \hat{\boldsymbol{\beta}}_{within}^{ols}$

If $\sigma_\alpha^2 \to 0$, $\psi^2 \to 1$, $\hat{\boldsymbol{\beta}}_{re}^{ols} \to \hat{\boldsymbol{\beta}}_{pool}^{ols}$ It is because

$$\begin{aligned}
\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}})(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}})' &= \sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)+(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}}))((\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)+(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}}))' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})' + \\
&\quad \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})'
\end{aligned}$$

Similarly,

$$\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}})(y_{it}-\bar{y}) = \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)(y_{it}-\bar{y}_i) + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})(\bar{y}_i-\bar{y})$$

Thus,

$$\begin{aligned}
\hat{\boldsymbol{\beta}}_{pool}^{ols} &= (\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}})(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}})')^{-1}(\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}})(y_{it}-\bar{y})) \\
&= (\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})')^{-1} \\
&\quad (\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)(y_{it}-\bar{y}_i) + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i-\bar{\boldsymbol{x}})(\bar{y}_i-\bar{y}))
\end{aligned}$$

So, pooled OLS estimator is an inefficient weighted average of within and between effects. RE estimator is an efficient weighted average of within and between effects. As RE model assumes $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma_\varepsilon^2\boldsymbol{I}_T]$,

$$Var(\widehat{\boldsymbol{\beta}}_{re}^{ols}) = \sigma_\varepsilon^2[\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}-\lambda\bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it}-\lambda\bar{\boldsymbol{x}}_i)']^{-1}$$

### 2.3.3 Between Effect Model and estimation of $\sigma_\alpha^2$

$$\begin{aligned}
\bar{y}_i &= \bar{\boldsymbol{x}}_i'\boldsymbol{\beta} + \overbrace{\alpha_i + \bar{\varepsilon}_i}^{v_i} \\
\sigma_B^2 = Var(v_i) &= Var(\alpha_i + \bar{\varepsilon}_i) \\
&= Var(\alpha_i) + Var(\bar{\varepsilon}_i) \\
&= Var(\alpha_i) + T^{-1}Var(\varepsilon_{it}) && \text{as } \varepsilon_{it} \text{ is serially uncorrelated}
\end{aligned}$$

$$\underbrace{Var(\alpha_i)}_{\sigma_\alpha^2} = \underbrace{Var(v_i)}_{\sigma_B^2} - T^{-1}\underbrace{Var(\varepsilon_{it})}_{\sigma_\varepsilon^2}$$

# 3 GMM Estimation of Linear Panel Model

## 3.1 Linear Panel Model

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}'_{i1} \\ \vdots \\ \boldsymbol{x}'_{iT} \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}$$
$$\boldsymbol{y}_i = \boldsymbol{X}_i \boldsymbol{\beta} + \boldsymbol{u}_i$$

## 3.2 Exogeneity Assumption

$$\mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{u}_i) = \boldsymbol{0}$$

$\boldsymbol{Z}_i$ is a $T$ x $r$ matrix. $r$ is the number of exogeneous variables in $\boldsymbol{X}_i$ plus the number of instrumental variables for endogeneous variables in $\boldsymbol{X}_i$. In GMM context, $r$ is also the number of moment conditions.

$K$ is the number of parameters.

$r \geq K$. If $r = K$, the model is just-identified, GMM is the same as MM; if $r > K$, the model is over-identified.

### 3.2.1 Summation Assumption

The weakest exogeneity assumption

$$\boldsymbol{Z}_i = \begin{pmatrix} \boldsymbol{z}'_{i1} \\ \vdots \\ \boldsymbol{z}'_{iT} \end{pmatrix}$$

$$\mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{u}_i) = \mathbb{E}(\begin{pmatrix} \boldsymbol{z}'_{i1} \\ \vdots \\ \boldsymbol{z}'_{iT} \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) = \mathbb{E}(\begin{pmatrix} \boldsymbol{z}_{i1} & \cdots & \boldsymbol{z}_{iT} \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) = \mathbb{E}(\sum_{t=1}^{T} \boldsymbol{z}_{it} u_{it}) = \boldsymbol{0}$$

### 3.2.2 Contemporaneous Exogeneity Assumption

Stronger

$$\boldsymbol{Z}_i = \begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix}$$

$$\begin{aligned}
\mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{u}_i) &= \mathbb{E}(\begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) \\
&= \mathbb{E}(\begin{pmatrix} \boldsymbol{z}_{i1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{z}_{iT} \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) \\
&= \mathbb{E}(\begin{pmatrix} \boldsymbol{z}_{i1} u_{i1} \\ \vdots \\ \boldsymbol{z}_{iT} u_{iT} \end{pmatrix}) \\
&= \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{i1}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT} u_{iT}) \end{pmatrix} = \boldsymbol{0}
\end{aligned}$$

### 3.2.3 Weak/Sequential Exogeneity Assumption

Stronger

$$\boldsymbol{Z}_i = \begin{pmatrix} \boldsymbol{z}'_{i1} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \begin{pmatrix} \boldsymbol{z}'_{i1} & \boldsymbol{z}'_{i2} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix} \end{pmatrix}$$

$$\begin{aligned}
\mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{u}_i) &= \mathbb{E}(\begin{pmatrix} \boldsymbol{z}'_{i1} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \begin{pmatrix} \boldsymbol{z}'_{i1} & \boldsymbol{z}'_{i2} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix} \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) \\
&= \mathbb{E}(\begin{pmatrix} \boldsymbol{z}_{i1} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \begin{pmatrix} \boldsymbol{z}_{i1} \\ \boldsymbol{z}_{i2} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \begin{pmatrix} \boldsymbol{z}_{i1} \\ \vdots \\ \boldsymbol{z}_{iT} \end{pmatrix} \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) \\
&= \mathbb{E}(\begin{pmatrix} \boldsymbol{z}_{i1} u_{i1} \\ \begin{pmatrix} \boldsymbol{z}_{i1} u_{i2} \\ \boldsymbol{z}_{i2} u_{i2} \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \boldsymbol{z}_{i1} u_{iT} \\ \vdots \\ \boldsymbol{z}_{iT} u_{iT} \end{pmatrix} \end{pmatrix}) = \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{i1}) \\ \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{i2}) \\ \mathbb{E}(\boldsymbol{z}_{i2} u_{i2}) \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{iT}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT} u_{iT}) \end{pmatrix} \end{pmatrix} = \boldsymbol{0}
\end{aligned}$$

which is equivalent as $\mathbb{E}(\boldsymbol{z}_{is} u_{it}) = \boldsymbol{0}$ for $s \leq t$.

Strong form of sequential exogeneity $\mathbb{E}(u_{it} | \boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1}) = 0$ implies weak form of sequential exogeneity $\mathbb{E}(\boldsymbol{z}_{is} u_{it}) = \boldsymbol{0}$ for $s \leq t$ as $\mathbb{E}(\boldsymbol{z}_{is} u_{it}) = \mathbb{E}(\mathbb{E}(\boldsymbol{z}_{is} u_{it} | \boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1})) = \mathbb{E}(\boldsymbol{z}_{is} \underbrace{\mathbb{E}(u_{it} | \boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1})}_{0}) = \boldsymbol{0}$ for $s \leq t$.

It also implies $Cov(\boldsymbol{z}_{is}, u_{it}) = \boldsymbol{0}$ for $s \leq t$ as $Cov(\boldsymbol{z}_{is}, u_{it}) = \underbrace{\mathbb{E}(\boldsymbol{z}_{is} u_{it})}_{\boldsymbol{0}} - \mathbb{E}(\boldsymbol{z}_{is})\mathbb{E}(u_{it}) = -\mathbb{E}(\boldsymbol{z}_{is})\mathbb{E}(\underbrace{\mathbb{E}(u_{it} | \boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1})}_{0}) = \boldsymbol{0}$ for $s \leq t$.

### 3.2.4 Strong/Strict Exogeneity Assumption

The strongest exogeneity assumption

$$\boldsymbol{Z}_i = \begin{pmatrix} \begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix} \end{pmatrix}$$

$$
\begin{aligned}
\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) &= \mathbb{E}(\begin{pmatrix} \begin{pmatrix}\boldsymbol{z}_{i1}' & \cdots & \boldsymbol{z}_{iT}'\end{pmatrix} & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \begin{pmatrix}\boldsymbol{z}_{i1}' & \cdots & \boldsymbol{z}_{iT}'\end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \begin{pmatrix}\boldsymbol{z}_{i1}' & \cdots & \boldsymbol{z}_{iT}'\end{pmatrix} \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) \\
&= \mathbb{E}(\begin{pmatrix} \begin{pmatrix}\boldsymbol{z}_{i1} \\ \vdots \\ \boldsymbol{z}_{iT}\end{pmatrix} & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \begin{pmatrix}\boldsymbol{z}_{i1} \\ \vdots \\ \boldsymbol{z}_{iT}\end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \begin{pmatrix}\boldsymbol{z}_{i1} \\ \vdots \\ \boldsymbol{z}_{iT}\end{pmatrix} \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}) \\
&= \mathbb{E}(\begin{pmatrix} \begin{pmatrix}\boldsymbol{z}_{i1}u_{i1} \\ \vdots \\ \boldsymbol{z}_{iT}u_{i1}\end{pmatrix} \\ \begin{pmatrix}\boldsymbol{z}_{i1}u_{i2} \\ \vdots \\ \boldsymbol{z}_{iT}u_{i2}\end{pmatrix} \\ \vdots \\ \begin{pmatrix}\boldsymbol{z}_{i1}u_{iT} \\ \vdots \\ \boldsymbol{z}_{iT}u_{iT}\end{pmatrix} \end{pmatrix}) \\
&= \begin{pmatrix} \begin{pmatrix}\mathbb{E}(\boldsymbol{z}_{i1}u_{i1}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT}u_{i1})\end{pmatrix} \\ \begin{pmatrix}\mathbb{E}(\boldsymbol{z}_{i1}u_{i2}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT}u_{i2})\end{pmatrix} \\ \vdots \\ \begin{pmatrix}\mathbb{E}(\boldsymbol{z}_{i1}u_{iT}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT}u_{iT})\end{pmatrix} \end{pmatrix} = \mathbf{0}
\end{aligned}
$$

which is equivalent as $\mathbb{E}(\boldsymbol{z}_{is}u_{it}) = \mathbf{0}$ for $s = 1, \cdots, T$

Strong form of strict exogeneity $\mathbb{E}(u_{it}|\boldsymbol{z}_{i1}, \cdots, \boldsymbol{z}_{iT}) = 0$ implies weak form of strict exogeneity $\mathbb{E}(\boldsymbol{z}_{is}u_{it}) = \mathbf{0}$ for $s = 1, \cdots, T$. Since for $s = 1, \cdots, T$,

$$
\begin{aligned}
\mathbb{E}(\boldsymbol{z}_{is}u_{it}) &= \mathbb{E}(\mathbb{E}(\boldsymbol{z}_{is}u_{it}|\boldsymbol{z}_{i1}, \cdots, \boldsymbol{z}_{iT})) \\
&= \mathbb{E}(\boldsymbol{z}_{is}\underbrace{\mathbb{E}(u_{it}|\boldsymbol{z}_{i1}, \cdots, \boldsymbol{z}_{iT})}_{0}) \\
&= \mathbf{0}
\end{aligned}
$$

## 3.3 GMM Estimator of Linear Panel Model

### 3.3.1 Unconditional Moment Condition

$$\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0)) = \mathbf{0}$$

where $\boldsymbol{\beta}_0$ is the true population parameter. So, $g(\boldsymbol{d}_i; \boldsymbol{\theta}_0) = \boldsymbol{Z}_i'\boldsymbol{u}_i = \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0)$

### 3.3.2 Objective / Loss Function

We want to find $\boldsymbol{\beta}$ from the parameter space such that the squared distance between $\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N$ and $\mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))$ i.e.,

$$
\begin{aligned}
&[\rho(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N, \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0)))]^2 && \text{where } \rho(.) \text{ is a metric function}\\
&= || \sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N - \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))||^2\\
&= (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N - \underbrace{\mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))}_{\mathbf{0}})'\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N - \underbrace{\mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))}_{\mathbf{0}})\\
&= (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)'\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N) \geq 0 && \text{as distance cannot be negative}
\end{aligned}
$$

is as close to the zero as possible. The distance is a function of $\boldsymbol{\beta}$ i.e.,

$$
Q_N(\boldsymbol{\beta}) := (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)'\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N) \geq 0
$$

If $\boldsymbol{W}_N$ is symmetric and positive definite, then $Q_N(\boldsymbol{\beta})$ is strictly convex. So, first order condition becomes sufficient and there is an unique minimizer.

### 3.3.3 Gradient Vector

$$
\begin{aligned}
\triangledown Q_N(\boldsymbol{\beta}) = \frac{\partial Q_N(\boldsymbol{\beta})}{\partial \boldsymbol{\beta}} &= \frac{\partial(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)'\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)}{\partial \boldsymbol{\beta}}\\
&= 2(\frac{\partial(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)}{\partial \boldsymbol{\beta}'})'\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)\\
&= 2[\sum_{i=1}^{N}(\frac{\partial \boldsymbol{Z}_i'\boldsymbol{y}_i}{\partial \boldsymbol{\beta}'} - \frac{\partial \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta}}{\partial \boldsymbol{\beta}'})/N]'\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)\\
&= 2[\sum_{i=1}^{N} -\frac{\partial \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta}}{\partial \boldsymbol{\beta}'}/N]'\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)\\
&= -2(1/N^2)\sum_{i=1}^{N}(\boldsymbol{Z}_i'\boldsymbol{X}_i)'\boldsymbol{W}_N\sum_{i=1}^{N}(\boldsymbol{Z}_i'\boldsymbol{y}_i - \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta})\\
&= -2(1/N^2)\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i''\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i - \sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta})\\
&= -2(1/N^2)[(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i) - (\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)\boldsymbol{\beta}]
\end{aligned}
$$

If $r = K$, both $(\frac{\partial(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)}{\partial \boldsymbol{\beta}'})'$ and $\boldsymbol{W}_N$ are square matrixes and invertible. In this case, FOC is $\triangledown Q_N(\widehat{\boldsymbol{\beta}}_{pmm}) = \sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\widehat{\boldsymbol{\beta}}_{pmm})/N = \mathbf{0}$ which is MM estimation.

### 3.3.4 First Order Condition

$$
\begin{aligned}
-2(1/N^2)[(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) - (\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)\widehat{\boldsymbol{\beta}}_{pgmm}] &= \boldsymbol{0} \\
(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) - (\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)\widehat{\boldsymbol{\beta}}_{pgmm} &= \boldsymbol{0} \\
(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) &= (\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)\widehat{\boldsymbol{\beta}}_{pgmm} \\
[(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)]^{-1}(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) &= \widehat{\boldsymbol{\beta}}_{pgmm}
\end{aligned}
$$

Special case: if $\boldsymbol{W}_N = (\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{Z}_i)^{-1}$,

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{pgmm} &= [(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\overbrace{(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{Z}_i)^{-1}(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)}^{\widehat{\boldsymbol{\Gamma}}_{2SLS}}]^{-1}\overbrace{(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{Z}_i)^{-1}}^{\widehat{\boldsymbol{\Gamma}}_{2SLS}'}(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) \\
&= [\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i\widehat{\boldsymbol{\Gamma}}_{2SLS}]^{-1}\widehat{\boldsymbol{\Gamma}}_{2SLS}'\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i \\
&= [\sum_{i=1}^N \boldsymbol{X}_i'\underbrace{\boldsymbol{Z}_i\widehat{\boldsymbol{\Gamma}}_{2SLS}}_{\widehat{\boldsymbol{X}}_i}]^{-1}\sum_{i=1}^N \underbrace{(\boldsymbol{Z}_i\widehat{\boldsymbol{\Gamma}}_{2SLS})'}_{\widehat{\boldsymbol{X}}_i'}\boldsymbol{y}_i = \widehat{\boldsymbol{\beta}}_{p2SLS}
\end{aligned}
$$

Special case: if $r = K$, the model is just-identified, GMM is the same as MM,

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{pmm} = \widehat{\boldsymbol{\beta}}_{pgmm} &= [(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)]^{-1}(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) \\
&= (\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)^{-1}\boldsymbol{W}_N^{-1}(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)^{-1}(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) \\
&= (\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)^{-1}(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) = \widehat{\boldsymbol{\beta}}_{piv}
\end{aligned}
$$

Special case: if all regressors are exogeneous: $\boldsymbol{Z}_i = \boldsymbol{X}_i$ (which implies $r = K$),

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{pgmm} &= \widehat{\boldsymbol{\beta}}_{piv} \\
&= (\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{X}_i)^{-1}(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{y}_i) = \widehat{\boldsymbol{\beta}}_{pols}
\end{aligned}
$$

$$
\begin{aligned}
\widehat{\boldsymbol{\beta}}_{pgmm} &= [(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{X}_i)]^{-1}(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^N \boldsymbol{Z}_i'\boldsymbol{y}_i) \\
&= [\begin{pmatrix}\boldsymbol{X}_1' & \cdots & \boldsymbol{X}_N'\end{pmatrix}\begin{pmatrix}\boldsymbol{Z}_1 \\ \vdots \\ \boldsymbol{Z}_N\end{pmatrix}\boldsymbol{W}_N\begin{pmatrix}\boldsymbol{Z}_1' & \cdots & \boldsymbol{Z}_N'\end{pmatrix}\begin{pmatrix}\boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N\end{pmatrix}]^{-1}\begin{pmatrix}\boldsymbol{X}_1' & \cdots & \boldsymbol{X}_N'\end{pmatrix}\begin{pmatrix}\boldsymbol{Z}_1 \\ \vdots \\ \boldsymbol{Z}_N\end{pmatrix}\boldsymbol{W}_N\begin{pmatrix}\boldsymbol{Z}_1' & \cdots & \boldsymbol{Z}_N'\end{pmatrix}\begin{pmatrix}\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N\end{pmatrix} \\
&= [\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1}\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{y}
\end{aligned}
$$

### 3.4 Conditional Variance of $\widehat{\boldsymbol{\beta}}_{pgmm}$

$$\begin{aligned}
Var(\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{y}|\boldsymbol{X},\boldsymbol{Z}) &= \boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'Var(\boldsymbol{y}|\boldsymbol{X},\boldsymbol{Z})(\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}')' \\
&= \boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'Var(\boldsymbol{X}\boldsymbol{\beta}+\boldsymbol{u}|\boldsymbol{X},\boldsymbol{Z})(\boldsymbol{Z}''\boldsymbol{W}_N'\boldsymbol{Z}'\boldsymbol{X}'') \\
&= \boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'Var(\boldsymbol{u}|\boldsymbol{X},\boldsymbol{Z})(\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}) \\
&= \boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N Var(\boldsymbol{Z}'\boldsymbol{u}|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X} \\
&= \boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\mathbb{E}((\boldsymbol{Z}'\boldsymbol{u}-\mathbb{E}(\boldsymbol{Z}'\boldsymbol{u}|\boldsymbol{X},\boldsymbol{Z}))(\boldsymbol{Z}'\boldsymbol{u}-\mathbb{E}(\boldsymbol{Z}'\boldsymbol{u}|\boldsymbol{X},\boldsymbol{Z}))'|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X} \\
&= \boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\mathbb{E}((\boldsymbol{Z}'\boldsymbol{u})(\boldsymbol{Z}'\boldsymbol{u})'|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X} \\
&= \boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\mathbb{E}(\boldsymbol{Z}'\boldsymbol{u}\boldsymbol{u}'\boldsymbol{Z}''|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}
\end{aligned}$$

$$\begin{aligned}
[\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1'} &= [\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]'^{-1} \\
&= [\boldsymbol{X}'\boldsymbol{Z}''\boldsymbol{W}_N'\boldsymbol{Z}'\boldsymbol{X}'']^{-1} \\
&= [\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1}
\end{aligned}$$

$$\begin{aligned}
Var(\widehat{\boldsymbol{\beta}}_{pgmm}|\boldsymbol{X},\boldsymbol{Z}) &= Var([\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1}\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{y}|\boldsymbol{X},\boldsymbol{Z}) \\
&= [\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1}Var(\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{y}|\boldsymbol{X},\boldsymbol{Z})[\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1'} \\
&= [\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1}\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\mathbb{E}(\boldsymbol{Z}'\boldsymbol{u}\boldsymbol{u}'Z|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}[\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1}
\end{aligned}$$

# 4 GMM Estimation of Fixed Effect Model

$$
\begin{aligned}
y_{it} &= \boldsymbol{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it} \\
\boldsymbol{y}_i &= \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i} \\
\boldsymbol{y} &= \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon}
\end{aligned}
$$

## 4.1 Assumption

$\alpha_i$ is potentially correlated with $\boldsymbol{X}_i$, so $\boldsymbol{u}_i$ is potentially correlated with $\boldsymbol{X}_i$

$\boldsymbol{\varepsilon}_i$ is also potentially correlated with $\boldsymbol{X}_i$, so $\boldsymbol{u}_i$ is potentially correlated with $\boldsymbol{X}_i$

Even after eliminating $\alpha_i$ by using any arbitrary operators $\boldsymbol{T}$, $\tilde{\boldsymbol{u}}_i := \boldsymbol{T}\boldsymbol{u}_i$ is still potentially correlated with $\tilde{\boldsymbol{X}}_i := \boldsymbol{T}\boldsymbol{X}_i$ because of the potential correlation between $\boldsymbol{\varepsilon}_i$ and $\boldsymbol{X}_i$. Thus, $\tilde{\boldsymbol{X}}_i$ is potentially endogeneous.

If $\tilde{\boldsymbol{X}}_i$ is endogeneous, OLS estimation is inconsistent and biased. We should use IV estimation (for just-identified case) and 2SLS estimation (for over-identified case). IV and 2SLS estimation are special cases of GMM estimation.

## 4.2 GMM Estimator of Fixed Effect Model

There exists a $\boldsymbol{T}$ such that $\boldsymbol{T}\boldsymbol{e} = \boldsymbol{0}$.

### 4.2.1 Transformed Model

$$
\begin{aligned}
\tilde{\boldsymbol{y}}_i &:= \boldsymbol{T}\boldsymbol{y}_i = \boldsymbol{T}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{u}_i) = \boldsymbol{T}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{T}\boldsymbol{u}_i := \tilde{\boldsymbol{X}}_i\boldsymbol{\beta} + \tilde{\boldsymbol{u}}_i \\
\tilde{\boldsymbol{u}}_i &:= \boldsymbol{T}\boldsymbol{u}_i = \boldsymbol{T}(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i) = \boldsymbol{T}\boldsymbol{e}\alpha_i + \boldsymbol{T}\boldsymbol{\varepsilon}_i = \boldsymbol{0} + \boldsymbol{T}\boldsymbol{\varepsilon}_i = \boldsymbol{T}\boldsymbol{\varepsilon}_i = \tilde{\boldsymbol{\varepsilon}}_i
\end{aligned}
$$

It is obvious that $\tilde{\boldsymbol{u}}_i = \boldsymbol{T}\boldsymbol{\varepsilon}_i$ is correlated with $\tilde{\boldsymbol{X}}_i := \boldsymbol{T}\boldsymbol{X}_i$ if $\boldsymbol{\varepsilon}_i$ is correlated with $\boldsymbol{X}_i$.

If $\boldsymbol{T} = \boldsymbol{Q} = \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}'$,

$$
\begin{aligned}
\tilde{\boldsymbol{y}}_i &= \tilde{\boldsymbol{X}}_i\boldsymbol{\beta} + \tilde{\boldsymbol{\varepsilon}}_i \\
(\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i) &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i) \\
(y_{it} - \bar{y}_i) &= (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + (\varepsilon_{it} - \bar{\varepsilon}_i)
\end{aligned}
$$

Under weak form of weak/sequential exogeneity assumption $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}$ for $s \le t$.

For $s \le t$, we have

$$
\begin{aligned}
\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) &= \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) - \mathbb{E}(\boldsymbol{z}_{is}\bar{\varepsilon}_i) \\
&= \boldsymbol{0} - \mathbb{E}(\boldsymbol{z}_{is}\sum_{t=1}^{T}\varepsilon_{it}/T) \\
&= -\frac{1}{T}\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1} + \cdots + \boldsymbol{z}_{is}\varepsilon_{i,s-1} + \boldsymbol{z}_{is}\varepsilon_{is} + \cdots + \boldsymbol{z}_{is}\varepsilon_{iT}) \\
&= -\frac{1}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{is}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{iT})) \\
&= -\frac{1}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \boldsymbol{0} + \cdots + \boldsymbol{0}) \\
&= -\frac{1}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}))
\end{aligned}
$$

So $\mathbb{E}(\boldsymbol{z}_{it}(\varepsilon_{it} - \bar{\varepsilon}_i))$ is not necessarily equal to zero under weak form of weak/sequential exogeneity assumption. If weak form of strong/strict exogeneity is assumed $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}\ \forall s$, then $\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) = \boldsymbol{0}\ \forall s$. So, $\boldsymbol{z}_{is}$, $s = 1, \cdots, T$ satisfy the exclusion restriction (exogeneity) requirement of valid instrument since $Cov(\boldsymbol{z}_{is}, \varepsilon_{it} - \bar{\varepsilon}_i) = \underbrace{\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i))}_{\boldsymbol{0}} - \mathbb{E}(\boldsymbol{z}_{is})\mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i) =$

$-\mathbb{E}(\boldsymbol{z}_{is})(\underbrace{\mathbb{E}(\varepsilon_{it})}_{0} - T^{-1}\sum_{t=1}^{T}\underbrace{\mathbb{E}(\varepsilon_{it})}_{0}) = \mathbf{0}\ \forall s$ (additionally assume $\mathbb{E}(\varepsilon_{it}) = 0$). So, we have

$$\begin{aligned}
\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) &= \mathbf{0} && \text{for } \forall s \\
\iff \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)) &= \mathbf{0} \\
\iff \mathbb{E}(\boldsymbol{Z}_i'\tilde{\boldsymbol{\varepsilon}}_i) &= \mathbf{0}
\end{aligned}$$

We can then apply IV estimation in GMM framework.

If $\boldsymbol{T} = \boldsymbol{\Delta}$

$$\begin{aligned}
\tilde{\boldsymbol{y}}_i &= \tilde{\boldsymbol{X}}_i\boldsymbol{\beta} + \tilde{\boldsymbol{\varepsilon}}_i \\
\boldsymbol{\Delta y}_i &= \boldsymbol{\Delta X}_i\boldsymbol{\beta} + \boldsymbol{\Delta\varepsilon}_i \\
(y_{it} - y_{i,t-1}) &= (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})'\boldsymbol{\beta} + (\varepsilon_{it} - \varepsilon_{i,t-1})
\end{aligned}$$

Under weak form of weak/sequential exogeneity assumption $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \mathbf{0}$ for $s \leq t$.

For $s < t$, we have

$$\begin{aligned}
\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \varepsilon_{i,t-1})) &= \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) - \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,t-1}) \\
&= \mathbf{0} - \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,t-1}) && \text{as } s < t \implies s \leq t \\
&= \mathbf{0} && \text{as } s < t \iff s \leq t-1
\end{aligned}$$

So, $\boldsymbol{z}_{is}$ for $s < t$ satisfy the exclusion restriction (exogeneity) requirement of valid instrument since $Cov(\boldsymbol{z}_{is}, \varepsilon_{it} - \varepsilon_{i,t-1}) = 0$ for $s < t$ (additionally assume $\mathbb{E}(\varepsilon_{it}) = 0$). Equivalently,

$$\boldsymbol{Z}_i = \begin{pmatrix}
t=2; \boldsymbol{z}_{i1}' & \mathbf{0} & \cdots & \mathbf{0} \\
\vdots & t=3; \begin{pmatrix}\boldsymbol{z}_{i1}' & \boldsymbol{z}_{i2}'\end{pmatrix} & \vdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
\mathbf{0} & \cdots & \mathbf{0} & t=T; \begin{pmatrix}\boldsymbol{z}_{i1}' & \cdots & \boldsymbol{z}_{i,T-1}'\end{pmatrix}
\end{pmatrix}$$

So, we have

$$\begin{aligned}
\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \varepsilon_{i,t-1})) &= \mathbf{0} && \text{for } s < t \\
\iff \mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Delta\varepsilon}_i) &= \mathbf{0} \\
\iff \mathbb{E}(\boldsymbol{Z}_i'\tilde{\boldsymbol{\varepsilon}}_i) &= \mathbf{0}
\end{aligned}$$

We can then apply IV estimation in GMM framework.

# 5 GMM Estimation of Random Effect Model

$$
\begin{aligned}
y_{it} &= \boldsymbol{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it} \\
\boldsymbol{y}_i &= \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i} \\
\boldsymbol{y} &= \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon}
\end{aligned}
$$

## 5.1 Assumption

$\alpha_i$ is not correlated with $\boldsymbol{X}_i$.

$\boldsymbol{\varepsilon}_i$ is potentially correlated with $\boldsymbol{X}_i$, so $\boldsymbol{u}_i$ is potentially correlated with $\boldsymbol{X}_i$ Thus, $\boldsymbol{X}_i$ is potentially endogeneous.

If $\boldsymbol{X}_i$ is endogeneous, OLS estimation is inconsistent and biased. We should use IV estimation (for just-identified case) and 2SLS estimation (for over-identified case). IV and 2SLS estimations are special cases of GMM estimation.

Assume

$$\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{Z}_i) = \boldsymbol{0}$$

Which is stronger than $\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{Z}_i) = \boldsymbol{0}$ implies $\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \boldsymbol{0}$

And assume

$$Var(\boldsymbol{u}_i|\boldsymbol{Z}_i) = \boldsymbol{\Omega}_i = \begin{pmatrix} \sigma_\alpha^2 + \sigma_\varepsilon^2 & \cdots & \sigma_\alpha^2 \\ \vdots & \ddots & \vdots \\ \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 + \sigma_\varepsilon^2 \end{pmatrix}$$

### 5.1.1 Optimal Moment Condition

$$
\begin{aligned}
\boldsymbol{D}_i &= \mathbb{E}(\frac{\partial \boldsymbol{u}_i'}{\partial \boldsymbol{\beta}}|\boldsymbol{Z}_i)Var(\boldsymbol{u}_i|\boldsymbol{Z}_i)^{-1} \\
&= \mathbb{E}(\frac{\partial (\boldsymbol{Z}_i\boldsymbol{\beta})'}{\partial \boldsymbol{\beta}}|\boldsymbol{Z}_i)\boldsymbol{\Omega}_i^{-1} \\
&= \mathbb{E}(\boldsymbol{Z}_i'|\boldsymbol{Z}_i)\boldsymbol{\Omega}_i^{-1} \\
&= \boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1}
\end{aligned}
$$

Optimal unconditional moment is

$$
\begin{aligned}
\mathbb{E}(\boldsymbol{D}_i\boldsymbol{u}_i) &= \boldsymbol{0} \\
\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1}\boldsymbol{u}_i) &= \boldsymbol{0} \\
\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) &= \boldsymbol{0} \\
\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i'^{-1/2}\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) &= \boldsymbol{0} \\
\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1/2'}\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) &= \boldsymbol{0} \\
\mathbb{E}((\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{Z}_i)'\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) &= \boldsymbol{0} \\
\sigma_\varepsilon^2\mathbb{E}((\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{Z}_i)'\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) &= \sigma_\varepsilon^2\boldsymbol{0} \\
\mathbb{E}((\sigma_\varepsilon\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{Z}_i)'\sigma_\varepsilon\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) &= \boldsymbol{0}
\end{aligned}
$$

This implies that the model should be transformed by $\sigma_\varepsilon\boldsymbol{\Omega}_i^{-1/2}$

## 5.2 GMM Estimator of Random Effect Model

### 5.2.1 Transformed Model

$$
\begin{aligned}
\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{y}_i &= \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + (\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)) = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{u}_i) = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{X}_i\boldsymbol{\beta} + \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{u}_i \\
(\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i) &= (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + [(1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)] \qquad \lambda = 1 - \psi = 1 - \frac{\sigma_\varepsilon}{\sqrt{T\sigma_\alpha^2 + \sigma_\varepsilon^2}} \\
(y_{it} - \lambda\bar{y}_i) &= (\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + [(1-\lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)]
\end{aligned}
$$

Under weak form of weak/sequential exogeneity assumption $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}$ for $s \leq t$.

For $s \leq t$, we have

$$\begin{aligned}
\mathbb{E}(\boldsymbol{z}_{is}[(1-\lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)]) &= \mathbb{E}(\boldsymbol{z}_{is}(1-\lambda)\alpha_i + \boldsymbol{z}_{is}(\varepsilon_{it} - \lambda\bar{\varepsilon}_i)) \\
&= (1-\lambda)\mathbb{E}(\boldsymbol{z}_{is}\alpha_i) + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) - \lambda\mathbb{E}(\boldsymbol{z}_{is}\bar{\varepsilon}_i) \\
&= (1-\lambda)\boldsymbol{0} + \boldsymbol{0} - \lambda E(\boldsymbol{z}_{is}\sum_{t=1}^{T}\varepsilon_{it}/T) \\
&= -\frac{\lambda}{T}\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1} + \cdots + \boldsymbol{z}_{is}\varepsilon_{i,s-1} + \boldsymbol{z}_{is}\varepsilon_{is} + \cdots + \boldsymbol{z}_{is}\varepsilon_{iT}) \\
&= -\frac{\lambda}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{is}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{iT})) \\
&= -\frac{\lambda}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \boldsymbol{0} + \cdots + \boldsymbol{0}) \\
&= -\frac{\lambda}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}))
\end{aligned}$$

So $\mathbb{E}(\boldsymbol{z}_{it}(\varepsilon_{it} - \bar{\varepsilon}_i))$ is not necessarily equal to zero under weak form of weak/sequential exogeneity assumption.

If weak form of strong/strict exogeneity assumption is assumed $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}\ \forall s$, then $\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) = \boldsymbol{0}\ \forall s$
So, $\boldsymbol{z}_{is}$, $s = 1, \cdots, T$ satisfy the exclusion restriction (exogeneity) requirement of valid instrument.

So, we have

$$\begin{aligned}
&\mathbb{E}(\boldsymbol{z}_{is}[(1-\lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)]) = \boldsymbol{0} && \text{for } \forall s \\
\iff\ &\mathbb{E}(\boldsymbol{Z}_i'[(1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)]) = \boldsymbol{0}
\end{aligned}$$

We can then apply IV estimation in GMM framework.

# 6 Dynamic Linear Panel Model

## 6.1 Assumption

### 6.1.1 Weak/Sequential Exogeneity

For $t = 2, \cdots, T$

$$\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i) = 0$$

This implies

$$\mathbb{E}(y_{is}\varepsilon_{it}) = 0,\ \mathbb{E}(\varepsilon_{it}) = 0 \quad and \quad \mathbb{E}(\alpha_i\varepsilon_{it}) = 0 \qquad \text{for } s < t$$

And

$$Cov(y_{is}, \varepsilon_{it}) = 0 \quad and \quad Cov(\alpha_i, \varepsilon_{it}) = 0 \qquad \text{for } s < t$$

It is because

$$\begin{aligned}
Cov(y_{is}, \varepsilon_{it}) &= \mathbb{E}(y_{is}\varepsilon_{it}) - \mathbb{E}(y_{is})\mathbb{E}(\varepsilon_{it}) \\
&= \mathbb{E}(\mathbb{E}(y_{is}\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)) - \mathbb{E}(y_{is})\mathbb{E}(\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)) \\
&= \mathbb{E}(y_{is}\underbrace{\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)}_{0}) - \mathbb{E}(y_{is})\mathbb{E}(\underbrace{\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)}_{0}) \qquad \text{as } s < t \\
&= 0
\end{aligned}$$

## 6.2 Model

### 6.2.1 No Transformation

$$y_{it} = \gamma y_{i,t-1} + \boldsymbol{x}'_{it}\boldsymbol{\beta} + \underbrace{(\alpha_i + \varepsilon_{it})}_{u_{it}}$$

$$\begin{aligned}
Cov(y_{i,t-1}, \alpha_i) &= Cov(\gamma y_{i,t-2} + \boldsymbol{x}'_{i,t-1}\boldsymbol{\beta} + \alpha_i + \varepsilon_{i,t-1}, \alpha_i) \\
&= \gamma Cov(y_{i,t-2}, \alpha_i) + Cov(\boldsymbol{x}'_{i,t-1}\boldsymbol{\beta}, \alpha_i) + Var(\alpha_i) + \underbrace{Cov(\varepsilon_{i,t-1}, \alpha_i)}_{0} \\
&= \gamma Cov(y_{i,t-2}, \alpha_i) + \boldsymbol{\beta}' Cov(\boldsymbol{x}_{i,t-1}, \alpha_i) + Var(\alpha_i) \\
&\neq 0 \qquad \text{assume } Cov(\boldsymbol{x}_{i,t-1}, \alpha_i) \neq 0 \text{ and } Var(\alpha_i) > 0
\end{aligned}$$

so that

$$\begin{aligned}
Cov(y_{i,t-1}, u_{it}) &= Cov(y_{i,t-1}, \alpha_i + \varepsilon_{it}) \\
&= \underbrace{Cov(y_{i,t-1}, \alpha_i)}_{\neq 0} + \underbrace{Cov(y_{i,t-1}, \varepsilon_{it})}_{0} \\
&\neq 0
\end{aligned}$$

The necessary condition for OLS estimator to be unbiased is $\mathbb{E}(u_{it}|y_{i,t-1}, \boldsymbol{x}_{it}) = 0$. As $\mathbb{E}(u_{it}|y_{i,t-1}, \boldsymbol{x}_{it}) = 0 \implies Cov(y_{i,t-1}, u_{it}) = 0$. As a result, $Cov(y_{i,t-1}, u_{it}) \neq 0 \implies \mathbb{E}(u_{it}|y_{i,t-1}, \boldsymbol{x}_{it}) \neq 0$. Thus, OLS estimator is biased.

### 6.2.2 Special case: no $\boldsymbol{x}_{it}$

$$y_{it} = \gamma y_{i,t-1} + \underbrace{(\alpha_i + \varepsilon_{it})}_{u_{it}}$$

The necessary condition for OLS estimator to be consistent is $\mathbb{E}(y_{i,t-1}u_{it}) = 0$. However,

$$\begin{aligned}
\mathbb{E}(y_{i,t-1}u_{it}) &= \mathbb{E}(y_{i,t-1}(\alpha_i + \varepsilon_{it})) \\
&= \mathbb{E}(y_{i,t-1}\alpha_i) + \underbrace{\mathbb{E}(y_{i,t-1}\varepsilon_{it})}_{0} > 0
\end{aligned}$$

$$\begin{aligned}
\mathbb{E}(y_{i,t-1}\alpha_i) &= \mathbb{E}((\gamma y_{i,t-2} + \alpha_i + \varepsilon_{i,t-1})\alpha_i) \\
&= \gamma\mathbb{E}(y_{i,t-2}\alpha_i) + \mathbb{E}(\alpha_i^2) + \mathbb{E}(\varepsilon_{i,t-1}\alpha_i) \\
&= \gamma\mathbb{E}((\gamma y_{i,t-3} + \alpha_i + \varepsilon_{i,t-2})\alpha_i) + \mathbb{E}(\alpha_i^2) + \mathbb{E}(\mathbb{E}(\varepsilon_{i,t-1}\alpha_i | y_{i,t-2}, \cdots, y_{i1}, \alpha_i)) \\
&= \gamma^2\mathbb{E}(y_{i,t-3}\alpha_i) + \gamma\mathbb{E}(\alpha_i^2) + \gamma\mathbb{E}(\varepsilon_{i,t-2}\alpha_i) + \mathbb{E}(\alpha_i^2) + \mathbb{E}(\alpha_i \underbrace{\mathbb{E}(\varepsilon_{i,t-1} | y_{i,t-2}, \cdots, y_{i1}, \alpha_i)}_{0}) \\
&= \gamma^2\mathbb{E}(y_{i,t-3}\alpha_i) + \gamma\mathbb{E}(\alpha_i^2) + \mathbb{E}(\alpha_i^2) \\
&\cdots \\
&= \gamma^{t-2}\mathbb{E}(y_{i,t-(t-2+1)}) + \gamma^{t-2-1}\mathbb{E}(\alpha_i^2) + \cdots + \mathbb{E}(\alpha_i^2) \\
&= \gamma^{t-2}\mathbb{E}(y_{i1}) + \gamma^{t-3}\mathbb{E}(\alpha_i^2) + \cdots + \mathbb{E}(\alpha_i^2) \\
&= \gamma^{t-2}y_{i1} + \gamma^{t-3}Var(\alpha_i) + \cdots + Var(\alpha_i) && y_{i1} \text{ is initial value and assume } \mathbb{E}(\alpha_i) = 0 \\
&> 0 && \text{assume } Var(\alpha_i) > 0,\ y_{i1} > 0 \text{ and } 0 < \gamma < 1
\end{aligned}$$

Thus, OLS estimator is inconsistent. The necessary condition for OLS estimator to be unbiased is $\mathbb{E}(u_{it}|y_{i,t-1}) = 0$. As $\mathbb{E}(u_{it}|y_{i,t-1}) = 0 \implies \mathbb{E}(y_{i,t-1}u_{it}) = 0$, $\mathbb{E}(y_{i,t-1}u_{it}) \neq 0 \implies \mathbb{E}(u_{it}|y_{i,t-1}) \neq 0$. Thus, OLS estimator is biased. It can also be seen by OVB formula.

$$\begin{aligned}
\gamma_{short} &= \frac{Cov(y_{it}, y_{i,t-1})}{Var(y_{i,t-1})} \\
&= \frac{Cov(\gamma_{long}y_{i,t-1} + \alpha_i + \varepsilon_{it}, y_{i,t-1})}{Var(y_{i,t-1})} \\
&= \gamma_{long} + \frac{Cov(\alpha_i, y_{i,t-1})}{Var(y_{i,t-1})} + \overbrace{\frac{Cov(\varepsilon_{it}, y_{i,t-1})}{Var(y_{i,t-1})}}^{0} \\
&= \gamma_{long} + \frac{Cov(\alpha_i, y_{i,t-1})}{Var(y_{i,t-1})}
\end{aligned}$$

$$\gamma_{short} - \gamma_{long} = \frac{Cov(\alpha_i, y_{i,t-1})}{Var(y_{i,t-1})} > 0 \qquad \text{if } Var(y_{i,t-1}) > 0$$

$$Cov(\alpha_i, y_{i,t-1}) = \mathbb{E}(\alpha_i y_{i,t-1}) - \mathbb{E}(\alpha_i)\mathbb{E}(y_{i,t-1}) > 0 \qquad \text{see above for } \mathbb{E}(\alpha_i y_{i,t-1}) > 0 \text{ and assume } \mathbb{E}(\alpha_i) = 0$$

Thus, OLS estimator is biased upward / over-estimate.

### 6.2.3 Within Transformation

$$y_{it} - \bar{y}_i = \gamma(y_{i,t-1} - \bar{y}_{i,-1}) + (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + (\varepsilon_{it} - \bar{\varepsilon}_i)$$

$$\begin{aligned}
Cov(y_{i,t-1}, \bar{\varepsilon}_i) &= Cov(\gamma y_{i,t-2} + \boldsymbol{x}'_{i,t-1}\boldsymbol{\beta} + \alpha_i + \varepsilon_{i,t-1}, T^{-1}\sum_{t=1}^{T}\varepsilon_{it}) \\
&\neq 0 && \text{since } \varepsilon_{i,t-1} \text{ is correlated with } T^{-1}\textstyle\sum_{t=1}^{T}\varepsilon_{it}
\end{aligned}$$

so that

$$Cov(y_{i,t-1} - \bar{y}_{i,-1}, \varepsilon_{it} - \bar{\varepsilon}_i) \neq 0$$

The necessary condition for FE estimator to be unbiased is $\mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i | y_{i,t-1} - \bar{y}_{i,-1}, \boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) = 0$. As $\mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i | y_{i,t-1} - \bar{y}_{i,-1}, \boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) = 0 \implies Cov(y_{i,t-1} - \bar{y}_{i,-1}, \varepsilon_{it} - \bar{\varepsilon}_i) = 0$. As a result, $Cov(y_{i,t-1} - \bar{y}_{i,-1}, \varepsilon_{it} - \bar{\varepsilon}_i) \neq 0 \implies \mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i | y_{i,t-1} - \bar{y}_{i,-1}, \boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) \neq 0$. Thus, FE estimator is biased.

#### 6.2.4 Special case: no $\boldsymbol{x}_{it}$

$$y_{it} - \bar{y}_i = \gamma(y_{i,t-1} - \bar{y}_{i,-1}) + (\varepsilon_{it} - \bar{\varepsilon}_i)$$

The bias is called Nickell (1981) bias / dynamic panel bias. If $\gamma > 0$, the bias must be negative. The bias converges to zero when $T \to \infty$.

#### 6.2.5 First Difference Transformation

$$\tilde{\boldsymbol{y}}_i = \tilde{\boldsymbol{X}}_i \boldsymbol{\delta} + \tilde{\boldsymbol{\varepsilon}}_i$$

$$\begin{pmatrix} y_{i3} - y_{i2} \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix} = \begin{pmatrix} y_{i2} - y_{i1} & (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2})' \\ \vdots & \\ y_{i,T-1} - y_{i,T-2} & (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1})' \end{pmatrix} \begin{pmatrix} \gamma \\ \boldsymbol{\beta} \end{pmatrix} + \begin{pmatrix} \varepsilon_{i3} - \varepsilon_{i2} \\ \vdots \\ \varepsilon_{iT} - \varepsilon_{i,T-1} \end{pmatrix}$$

$$y_{it} - y_{i,t-1} = \gamma(y_{i,t-1} - y_{i,t-2}) + (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})'\boldsymbol{\beta} + (\varepsilon_{it} - \varepsilon_{i,t-1}) \qquad t \geq 3$$

$$\begin{aligned}
Cov(y_{i,t-1} - y_{i,t-2}, \varepsilon_{it} - \varepsilon_{i,t-1}) &= Cov(y_{i,t-1}, \varepsilon_{it}) - Cov(y_{i,t-1}, \varepsilon_{i,t-1}) - Cov(y_{i,t-2}, \varepsilon_{it}) + Cov(y_{i,t-2}, \varepsilon_{i,t-1}) \\
&= 0 - Cov(y_{i,t-1}, \varepsilon_{i,t-1}) - 0 + 0 && \text{as } Cov(y_{is}, \varepsilon_{it}) = 0 \text{ for } s < t \\
&= -Cov(\gamma y_{i,t-2} + \boldsymbol{x}'_{i,t-1}\boldsymbol{\beta} + \alpha_i + \varepsilon_{i,t-1}, \varepsilon_{i,t-1}) \\
&= -\gamma \underbrace{Cov(y_{i,t-2}, \varepsilon_{i,t-1})}_{0} - \boldsymbol{\beta}' \underbrace{Cov(\boldsymbol{x}_{i,t-1}, \varepsilon_{i,t-1})}_{0} - \underbrace{Cov(\alpha_i, \varepsilon_{i,t-1})}_{0} - Var(\varepsilon_{i,t-1}) \\
&< 0 && \text{assume } Var(\varepsilon_{i,t-1}) > 0
\end{aligned}$$

The necessary condition for FD estimator to be unbiased is $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1} | y_{i,t-1} - y_{i,t-2}, \boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1}) = 0$. As $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1} | y_{i,t-1} - y_{i,t-2}, \boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1}) = 0 \implies Cov(y_{i,t-1} - y_{i,t-2}, \varepsilon_{it} - \varepsilon_{i,t-1}) = 0$. As a result, $Cov(y_{i,t-1} - y_{i,t-2}, \varepsilon_{it} - \varepsilon_{i,t-1}) \neq 0 \implies \mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1} | y_{i,t-1} - y_{i,t-2}, \boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1}) \neq 0$. Thus, FD estimator is biased.

#### 6.2.6 Special case: no $\boldsymbol{x}_{it}$

$$y_{it} - y_{i,t-1} = \gamma(y_{i,t-1} - y_{i,t-2}) + (\varepsilon_{it} - \varepsilon_{i,t-1})$$

The necessary condition for FD estimator to be consistent is $\mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) = 0$. However,

$$\begin{aligned}
\mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) &= \mathbb{E}(y_{i,t-1}\varepsilon_{it}) - \mathbb{E}(y_{i,t-1}\varepsilon_{i,t-1}) - \mathbb{E}(y_{i,t-2}\varepsilon_{it}) + \mathbb{E}(y_{i,t-2}\varepsilon_{i,t-1}) \\
&= 0 - \mathbb{E}(y_{i,t-1}\varepsilon_{i,t-1}) - 0 + 0 && \text{as } \mathbb{E}(y_{is}\varepsilon_{it}) = 0 \text{ for } s < t \\
&= -\mathbb{E}((\gamma y_{i,t-2} + \alpha_i + \varepsilon_{i,t-1})\varepsilon_{i,t-1}) \\
&= -\gamma \underbrace{\mathbb{E}(y_{i,t-2}\varepsilon_{i,t-1})}_{0} - \underbrace{\mathbb{E}(\alpha_i \varepsilon_{i,t-1})}_{0} - \mathbb{E}(\varepsilon_{i,t-1}^2) \\
&= -Var(\varepsilon_{i,t-1}) && \text{as } \mathbb{E}(\varepsilon_{i,t-1}) = 0 \\
&< 0 && \text{assume } Var(\varepsilon_{i,t-1}) > 0
\end{aligned}$$

Thus, FD estimator is inconsistent. The necessary condition for FD estimator to be unbiased is $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1} | y_{i,t-1} - y_{i,t-2}) = 0$. As $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1} | y_{i,t-1} - y_{i,t-2}) = 0 \implies \mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) = 0$, $\mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) \neq 0 \implies \mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1} | y_{i,t-1} - y_{i,t-2}) \neq 0$. Thus, FD estimator is biased.

Thus, IV estimation (for just-identified case) or 2SLS estimation (for over-identified case) is applied. IV and 2SLS estimations are special cases of GMM estimation.

Under weak/sequential exogeneity, $Cov(y_{is}, \varepsilon_{it}) = 0$ for $s < t$. This implies for $s < t-1 \iff s \leq t-2$

$$\begin{aligned}
Cov(y_{is}, \varepsilon_{it} - \varepsilon_{it-1}) &= Cov(y_{is}, \varepsilon_{it}) - Cov(y_{is}, \varepsilon_{i,t-1}) \\
&= 0 - Cov(y_{is}, \varepsilon_{i,t-1}) && \text{as } s < t-1 \implies s < t \\
&= 0 && \text{as } s < t-1
\end{aligned}$$

Note that $Cov(y_{is}, \varepsilon_{it} - \varepsilon_{i,t-1}) = 0 \implies \mathbb{E}(y_{is}(\varepsilon_{it} - \varepsilon_{i,t-1})) = 0$ as $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}) = 0$ under weak/sequential exogeneity. So, $y_{is}$ for $s \leq t-2$ satisfy the exclusion restriction (exogeneity) requirement of valid instrument. i.e.,

$$\begin{aligned}
\tilde{\boldsymbol{z}}'_{i3} =& (y_{i1}, \Delta \boldsymbol{x}'_{i3}) && \text{at } t=3 \\
\tilde{\boldsymbol{z}}'_{i4} =& (y_{i1}, y_{i2}, \Delta \boldsymbol{x}'_{i4}) && \text{at } t=4 \\
& \cdots \\
\tilde{\boldsymbol{z}}'_{iT} =& (y_{i1}, \cdots, y_{i,T-2}, \Delta \boldsymbol{x}'_{iT}) && \text{at } t=T
\end{aligned}$$

That is, $\tilde{\boldsymbol{z}}'_{it} = [y_{i1}, \cdots, y_{i,t-2}, \Delta \boldsymbol{x}'_{it}]$. $\boldsymbol{Z}_i = \begin{pmatrix} \tilde{\boldsymbol{z}}'_{i3} & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \tilde{\boldsymbol{z}}'_{i4} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \tilde{\boldsymbol{z}}'_{iT} \end{pmatrix}$

So, we have

$$\begin{aligned}
&\mathbb{E}(\tilde{\boldsymbol{z}}_{it}(\varepsilon_{it} - \varepsilon_{i,t-1})) = \mathbf{0} \\
\iff &\mathbb{E}(\boldsymbol{Z}'_i \Delta \boldsymbol{\varepsilon}_i) = \mathbf{0}
\end{aligned}$$

We can then apply 2SLS estimation in GMM framework. This is the same as Arellano-Bond estimator with 2SLS weight.

### 6.2.7 Anderson-Hsiao Estimator

Anderson & Hsiao (1981) considers a special case $y_{is}$ for $s = t-2$ i.e., $y_{i,t-2}$ as the instrument since they not only satisfy the exclusion restriction (exogeneity) requirement but also satisfy the relevancy requirement of valid instrument i.e., correlates with $y_{i,t-1} - y_{i,t-2}$. Thus, $\tilde{\boldsymbol{z}}'_{it} = [y_{i,t-2}, \Delta \boldsymbol{x}'_{it}]$

$$\boldsymbol{Z}_i = \begin{pmatrix} \begin{pmatrix} y_{i1} & \Delta \boldsymbol{x}'_{i3} \end{pmatrix} & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \begin{pmatrix} y_{i2} & \Delta \boldsymbol{x}'_{i4} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \begin{pmatrix} y_{i,T-2} & \Delta \boldsymbol{x}'_{iT} \end{pmatrix} \end{pmatrix}$$

and

$$\tilde{\boldsymbol{z}}'_{it} = [\underbrace{\Delta y_{i,t-2}}_{y_{i,t-2} - y_{i,t-3}}, \Delta \boldsymbol{x}'_{it}]$$

$$\boldsymbol{Z}_i = \begin{pmatrix} \begin{pmatrix} \Delta y_{i2} & \Delta \boldsymbol{x}'_{i4} \end{pmatrix} & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \begin{pmatrix} \Delta y_{i3} & \Delta \boldsymbol{x}'_{i5} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \begin{pmatrix} \Delta y_{i,T-2} & \Delta \boldsymbol{x}'_{iT} \end{pmatrix} \end{pmatrix}$$

As only one instrument is used at each $t$, the number of moments is equal to the number of parameters i.e., $r = K$. In such case, GMM estimation = MM estimation = IV estimation.

$$\widehat{\boldsymbol{\delta}}_{AH}^{pgmm} = [\sum_{i=1}^{N} \boldsymbol{Z}'_i \tilde{\boldsymbol{X}}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{Z}'_i \tilde{\boldsymbol{y}}_i = \widehat{\boldsymbol{\delta}}_{AH}^{piv}$$

### 6.2.8 Arellano-Bond Estimator

Arellano & Bond (1991) considers all the possible cases i.e., $y_{is}$ for $s \leq t-2$. Except $t = 3$, more than one instruments are used, number of moments is larger than the number of parameters i.e., $r > K$. GMM estimation is 2SLS estimation if $\boldsymbol{W}_N = (\sum_{i=1}^{N} \boldsymbol{Z}'_i \boldsymbol{Z}_i)^{-1}$.

$$\tilde{\boldsymbol{z}}'_{it} = [y_{i1}, \cdots, y_{i,t-2}, \Delta \boldsymbol{x}'_{it}]$$

$$\boldsymbol{Z}_i = \begin{pmatrix} \begin{pmatrix} y_{i1} & \Delta \boldsymbol{x}'_{i3} \end{pmatrix} & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \begin{pmatrix} y_{i1} & y_{i2} & \Delta \boldsymbol{x}'_{i4} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \begin{pmatrix} y_{i1} & \cdots & y_{i,T-2} & \Delta \boldsymbol{x}'_{iT} \end{pmatrix} \end{pmatrix}$$

$$\widehat{\boldsymbol{\delta}}_{AB}^{pgmm} = [(\sum_{i=1}^{N} \tilde{\boldsymbol{X}}_i' \boldsymbol{Z}_i) \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i' \tilde{\boldsymbol{X}}_i)]^{-1} (\sum_{i=1}^{N} \tilde{\boldsymbol{X}}_i' \boldsymbol{Z}_i) \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i' \tilde{\boldsymbol{y}}_i)$$

If $\boldsymbol{W}_N = (\sum_{i=1}^{N} \boldsymbol{Z}_i' \boldsymbol{Z}_i)^{-1}$, $\widehat{\boldsymbol{\delta}}_{AB}^{pgmm} = \widehat{\boldsymbol{\delta}}_{AB}^{2SLS}$

If $\boldsymbol{W}_N = \widehat{\boldsymbol{S}}^{-1}$, $\widehat{\boldsymbol{\delta}}_{AB}^{pgmm} = \widehat{\boldsymbol{\delta}}_{AB}^{opgmm}$

# 7 Pooled Model and Clustered Standard Error

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \alpha_i + \varepsilon_{it} \qquad \text{Level 1}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}'_{i1} \\ \vdots \\ \boldsymbol{x}'_{iT} \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \alpha_i + \begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$

$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i} \qquad \text{Level 2}$$

$$\begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} = \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{pmatrix} + \begin{pmatrix} \boldsymbol{\varepsilon}_1 \\ \vdots \\ \boldsymbol{\varepsilon}_N \end{pmatrix}$$

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon} \qquad \text{Level 3}$$

where $\alpha_i$ is unobserved heterogeneity, $\boldsymbol{\varepsilon}_i$ is idiosyncratic error, $\boldsymbol{u}_i$ is composite error.

If $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0$, OLS estimator is likely to be unbiased and consistent.
$\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies \mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \mathbb{E}(\boldsymbol{X}'_i\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{X}'_i\boldsymbol{e}\mathbb{E}(\alpha_i|\boldsymbol{X}) + \mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{0}$. Thus, the necessary condition for OLS estimator to be unbiased is satisfied if $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0$

$\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{X}'_i\boldsymbol{u}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{X}'_i\boldsymbol{u}_i) = \mathbb{E}(\mathbb{E}(\boldsymbol{X}'_i\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}'_i\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}'_i\boldsymbol{0}) = \boldsymbol{0}$. Thus, the necessary condition for OLS estimator to be consistent is satisfied if $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0$.

$\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies \mathbb{E}(\alpha_i\boldsymbol{X}_i) = \boldsymbol{0}$ and $\mathbb{E}(\alpha_i) = 0$. Thus, $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies Cov(\alpha_i, \boldsymbol{X}_i) = \boldsymbol{0}$ as $Cov(\alpha_i, \boldsymbol{X}_i) = \mathbb{E}(\alpha_i\boldsymbol{X}_i) - \mathbb{E}(\alpha_i)\mathbb{E}(\boldsymbol{X}_i) = \boldsymbol{0}$.

$$\begin{aligned} \widehat{\boldsymbol{\beta}}^{ols}_{pooled} &= [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{y}_i && \text{Level 2} \\ &= [\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1} \sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}y_{it} && \text{Level 1} \end{aligned}$$

As pooled model does not perform any transformation before OLS estimation, so $\boldsymbol{Q} = \boldsymbol{I}$.

$$\begin{aligned} Var(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) &= [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{I}'\boldsymbol{I}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{I}'Var(\boldsymbol{I}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{I}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{I}'\boldsymbol{I}\boldsymbol{X}_i]^{-1} \\ &= [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}'_iVar(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1} \end{aligned}$$

If $\varepsilon_{it}$ is homoskedasticity and serially uncorrelated across t i.e., $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma^2_\varepsilon\boldsymbol{I}_T$ (further assume independence of $i$ and strict exogeneity), we have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma^2_\varepsilon\boldsymbol{I}_T]$

$$\begin{aligned} &= \sigma^2_\varepsilon[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1} \\ &= \sigma^2_\varepsilon[\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1} \end{aligned}$$

If $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{\Omega}_i$, we have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim inid\ [\boldsymbol{0}, \boldsymbol{\Omega}_i]$

$$\begin{aligned} &= [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}'_i \overbrace{\mathbb{E}[\boldsymbol{\varepsilon}_i\boldsymbol{\varepsilon}'_i|\boldsymbol{X}_i]}^{\boldsymbol{\Omega}_i} \boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1} \\ &= [\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1} \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T} \boldsymbol{x}_{it}\mathbb{E}[\varepsilon_{it}\varepsilon_{is}|\boldsymbol{X}_i]\boldsymbol{x}'_{is}[\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1} \end{aligned}$$

## 7.1 Petersen (2009) Simulation Result

### 7.1.1 Only individual fixed effect

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \alpha_i + \varepsilon_{it}$$

If there is only $\alpha_i$ (individual fixed effect) and $\alpha_i$ is not correlated with $\boldsymbol{x}_{it}$ (so no OVB), OLS estimator is unbiased and clustered standard error clustered by individual is unbiased. In contrast, conventional standard error, White standard error, Newey-West standard error, Fama-Macbeth standard error are biased downward (over-rejection).

### 7.1.2 Only time fixed effect

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \gamma_t + \varepsilon_{it}$$

If there is only $\gamma_t$ (time fixed effect) and $\gamma_t$ is not correlated with $\boldsymbol{x}_{it}$ (so no OVB), OLS estimator is unbiased and Fama-Macbeth standard error and clustered standard error clustered by time (only if $T$ is large) is unbiased. In contrast, conventional standard error are biased downward (over-rejection).

### 7.1.3 Both individual and time fixed effect

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \alpha_i + \gamma_t + \varepsilon_{it}$$

Clustered standard error clustered by both individual and time is unbiased. Cameron, Gelbach, & Miller (2011), and Thompson (2011) suggests clustered standard error clustered by both individual and time = Clustered standard error clustered by individual + Clustered standard error clustered by time - White standard error. Simulation result seems work.

## 7.2 Clustering Problem

### 7.2.1 Block bootstrapping

Suggested by MacKinnon, Nielsen, & Webb (2022).

### 7.2.2 Clustered standard error with independence of $i$ (Liang & Zeger, 1986; Arellano, 1987)

Clustered standard error can handle both heteroscedasticity and serial correlation within a cluster / group.

$$\widehat{Var}(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{i=1}^{N}\boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}'_i\widehat{\boldsymbol{\Omega}}_i\boldsymbol{X}_i[\sum_{i=1}^{N}\boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}$$

$$\widehat{\boldsymbol{\Omega}}_i = \widehat{\boldsymbol{\varepsilon}}_i\widehat{\boldsymbol{\varepsilon}}'_i = \begin{pmatrix} \hat{\varepsilon}^2_{i1} & \hat{\varepsilon}_{i1}\hat{\varepsilon}_{i2} & \cdots & \hat{\varepsilon}_{i1}\hat{\varepsilon}_{iT} \\ \vdots & \hat{\varepsilon}^2_{i2} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\varepsilon}_{iT}\hat{\varepsilon}_{i1} & \cdots & \hat{\varepsilon}_{iT}\hat{\varepsilon}_{i,T-1} & \hat{\varepsilon}^2_{iT} \end{pmatrix}$$

$$\widehat{\boldsymbol{\Omega}} = \begin{pmatrix} \widehat{\boldsymbol{\Omega}}_1 & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \widehat{\boldsymbol{\Omega}}_2 & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \widehat{\boldsymbol{\Omega}}_N \end{pmatrix}$$

$$\begin{aligned}\widehat{Var}(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) &= [\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T}\boldsymbol{x}_{it}\hat{\varepsilon}_{it}\hat{\varepsilon}_{is}\boldsymbol{x}'_{is}[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1} \\ &= [\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}(\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\hat{\varepsilon}^2_{it}\boldsymbol{x}'_{it}+ \\ &\quad \sum_{l=1}^{T}[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\hat{\varepsilon}_{it}\hat{\varepsilon}_{i,t-l}\boldsymbol{x}'_{i,t-l} + \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}\hat{\varepsilon}_{it}\hat{\varepsilon}_{i,t-l}\boldsymbol{x}'_{i,t-l})'])[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}\end{aligned}$$

It is the panel generalization of Eicker-Huber-White estimator (White, 1980). If there is no serial correlation within the cluster / group, clustered standard error reduces to the exact form of Eicker-Huber-White estimator i.e.,

$$\begin{aligned}\widehat{Var}(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) &= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i' diag(\hat{\varepsilon}_i^2)\boldsymbol{X}_i[\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{X}_i]^{-1} \\ &= [\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\hat{\varepsilon}_{it}^2\boldsymbol{x}_{it}'[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}\end{aligned}$$

A weight can also be added to clustered standard error, this generalizes the Newey-West estimator (Newey & West, 1987).

$$\widehat{Var}(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T}\boldsymbol{x}_{it}w_{t,s}\hat{\varepsilon}_{it}\hat{\varepsilon}_{is}\boldsymbol{x}_{is}'[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}$$

where

$$w_{t,s} = \begin{cases} 1-\frac{|s-t|}{L+1} & \text{if } |s-t| \le L \\ 0 & \text{otherwise}\end{cases}$$

This can also be written as

$$\begin{aligned}\widehat{Var}(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}(&\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\hat{\varepsilon}_{it}^2\boldsymbol{x}_{it}' + \\ &\sum_{l=1}^{L}w_l[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\hat{\varepsilon}_{it}\hat{\varepsilon}_{i,t-l}\boldsymbol{x}_{i,t-l}' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it}\hat{\varepsilon}_{it}\hat{\varepsilon}_{i,t-l}\boldsymbol{x}_{i,t-l}')'])[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}\end{aligned}$$

Petersen (2009) finds that this adjustment is worser than the one without weight.

Finite sample adjustment e.g., $\frac{N}{N-1}\frac{T-1}{T-K}$ is multiplied in Stata. This leads to the generalization of HC1 in MacKinnon & White (1985). If $N$ (the number of cluster) is small, it is inconsistent because law of large number cannot be applied (even $T \to \infty$). However, we can adjust it by Bell & McCaffrey (2002)'s Bias-Reduced Linearization (BRL) adjustment which is the generalization of HC2, and using t-distribution with $N-K$ degree of freedom, instead of standard normal distribution.

In BRL adjustment, we replace $\widehat{\boldsymbol{\varepsilon}}_i$ by

$$\tilde{\boldsymbol{\varepsilon}}_i = \boldsymbol{A}_i\widehat{\boldsymbol{\varepsilon}}_i$$

where $\boldsymbol{A}_i'\boldsymbol{A}_i = (\boldsymbol{I}_T - \boldsymbol{H}_i)^{-1}$ where $\boldsymbol{H}_i = \boldsymbol{X}_i(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}_i'$ the projection/hat matrix.

There are many possible $\boldsymbol{A}_i$, Bell & McCaffrey (2002) uses eigen-decomposition of the inverse of the residual marker $\boldsymbol{I}_T - \boldsymbol{H}_i$ i.e.,

$$\begin{aligned}(\boldsymbol{I}_T - \boldsymbol{H}_i)^{-1} &= \boldsymbol{P}\boldsymbol{\Lambda}\boldsymbol{P}' \\ &= \boldsymbol{P}\boldsymbol{\Lambda}^{1/2}\boldsymbol{\Lambda}^{1/2}\boldsymbol{P}' \\ &= \boldsymbol{P}\boldsymbol{\Lambda}^{1/2}\boldsymbol{\Lambda}^{1/2'}\boldsymbol{P}' \\ &= \boldsymbol{P}\boldsymbol{\Lambda}^{1/2}(\boldsymbol{P}\boldsymbol{\Lambda}^{1/2})' \\ &= \boldsymbol{A}'\boldsymbol{A}''\end{aligned}$$

where $\boldsymbol{P}$ is a matrix in which vectors are eigenvectors; $\boldsymbol{\Lambda}$ is a diagonal matrix with eigenvalues items.

### 7.2.3 Clustered standard error with dependence of $i$ (Driscoll & Kraay, 1998)

It is called Spatial Correlation Consistent (SCC) estimator,

$$\widehat{Var}(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T}\boldsymbol{x}_{it}w_{t,s}\hat{\varepsilon}_{it}\hat{\varepsilon}_{js}\boldsymbol{x}_{js}'[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}_{it}']^{-1}$$

where

$$w_{t,s} = \begin{cases} 1-\frac{|s-t|}{L+1} & \text{if } |s-t| \le L \\ 0 & \text{otherwise}\end{cases}$$

This can also be written as

$$\widehat{Var}(\widehat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{t=1}^{T} \boldsymbol{X}_t'\boldsymbol{X}_t]^{-1}(\sum_{t=1}^{T} \boldsymbol{X}_t'\widehat{\boldsymbol{\varepsilon}}_t\widehat{\boldsymbol{\varepsilon}}_t'\boldsymbol{X}_t + \sum_{l=1}^{L} w_l[\sum_{t=1}^{T} \boldsymbol{X}_t'\widehat{\boldsymbol{\varepsilon}}_t\widehat{\boldsymbol{\varepsilon}}_{t-l}'\boldsymbol{X}_{t-l} + \sum_{t=1}^{T}(\boldsymbol{X}_t'\widehat{\boldsymbol{\varepsilon}}_t\widehat{\boldsymbol{\varepsilon}}_{t-l}'\boldsymbol{X}_{t-l})'])[\sum_{t=1}^{T} \boldsymbol{X}_t'\boldsymbol{X}_t]^{-1}$$

It requires large $T$. $L$ is up to you.

# 8 References


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# 9 Appendix - R Code

```r
library(lmtest)
library(plm)
library(fastDummies)
library(tidyverse)

set.seed(15)

gen_long_data <- function (N, T, var_gamma_i) {
  df <- tibble(.rows = N) %>% mutate(i = seq_len(N))
  df["gamma_i"] <- rnorm(N, mean = 0, sd = sqrt(var_gamma_i))

  for (t in seq_len(T)) {
    df[str_c("x_i", t)] <-
      df[["gamma_i"]] + rnorm(N, mean = 0, sd = sqrt(1 - var_gamma_i))

    df[str_c("y_i", t)] <-
      2 + df[[str_c("x_i", t)]] * 2 + df[["gamma_i"]] + rnorm(N, mean = 0, sd = sqrt(4 - var_gamma_i))
  }

  df %>%
    select(-gamma_i) %>%
    pivot_longer(
      cols = starts_with(c("y_i", "x_i")),
      names_to = c(".value", "t"),
      names_sep = "_i"
    )
}

long_data <-
  gen_long_data(100, 5, 0.1) %>%
  mutate(t = as.numeric(t)) %>%
  dummy_cols(select_columns = "i")

long_data_plm <- long_data %>% pdata.frame(index = c("i", "t"))

# within / FE estimator
plm(y ~ x, model = "within", effect = "individual", data = long_data_plm) %>%
  coeftest(., vcov = plm::vcovHC(., type = "HC1", cluster = "group"))

# first difference estimator
plm(y ~ x, model = "fd", effect = "individual", data = long_data_plm) %>%
  coeftest(., vcov = plm::vcovHC(., type = "HC1", cluster = "group"))

# LSDV estimator
plm(y ~ . + 0, model = "pooling", data = long_data_plm %>% select(-i, -t)) %>%
  coeftest(., vcov = plm::vcovHC(., type = "HC1", cluster = "group"))

# GLS / RE estimator
plm(y ~ x, model = "random", effect = "individual", data = long_data_plm) %>% coeftest()

# Pooled OLS with clustered standard error
plm(y ~ x, model = "pooling", data = long_data_plm) %>%
  coeftest(., vcov = plm::vcovHC(., type = "HC1", cluster = "group"))

# Pooled OLS with BRL adjusted clustered standard error
plm(y ~ x, model = "pooling", data = long_data_plm) %>%
  coeftest(., vcov = plm::vcovHC(., type = "HC2", cluster = "group"))
```