Assignment 1

Weihao Li

2020/8/29

1

(a)

$X_T = \overline{Y}_T - \mu_0$ is of order $T^{-\frac{1}{2}}$ in probability. $T^{-\frac{1}{2}}$ is a deterministic sequence of T that converges to 0 as $T \to \infty$.

Proof:

By definition of $O_p(.)$,

if for every $\varepsilon > 0$, there exists a constant M_ε, such that:

$$\underset{T}{sup} Pr(|\frac{X_T}{R_T}| > M_\varepsilon) < \varepsilon$$

then we can write:

$$X_T = O_p(R_T)$$

We know

$$\sqrt{T}(\overline{Y}_T - \mu_0) = O_p(1)$$

$\implies$

$$\underset{T}{sup} Pr(|\frac{\sqrt{T}(\overline{Y}_T - \mu_0)}{1}| > M_\varepsilon) < \varepsilon$$
$$\underset{T}{sup} Pr(|\frac{(\overline{Y}_T - \mu_0)}{\frac{1}{\sqrt{T}}}| > M_\varepsilon) < \varepsilon$$
$$\underset{T}{sup} Pr(|\frac{(\overline{Y}_T - \mu_0)}{T^{-\frac{1}{2}}}| > M_\varepsilon) < \varepsilon$$
$$(\overline{Y}_T - \mu_0) = X_T = O_p(T^{-\frac{1}{2}})$$

(b)

$X_T = \overline{Y}_T - \mu_0$ is of smaller order in probability than $T^{-\frac{1}{4}}$

Proof:

By definition of $o_p(.)$,

if for every $\varepsilon > 0$,

$$\lim_{T\to\infty} Pr(|\frac{X_T}{R_T} - 0| > \varepsilon) = 0$$

then we can write:

$$X_T = o_p(R_T)$$

$$\begin{aligned}\frac{\overline{Y}_T - \mu_0}{T^{-\frac{1}{4}}} &= T^{\frac{1}{4}}(\overline{Y}_T - \mu_0)\\ &= T^{-\frac{1}{4}}\sqrt{T}(\overline{Y}_T - \mu_0)\end{aligned}$$

Given $\sqrt{T}(\overline{Y}_T - \mu_0) = O_p(1)$ and $T^{-\frac{1}{4}} = o_p(1)$. Then using the rules of engagement $O_p(1)o_p(1) = o_p(1)$, $T^{-\frac{1}{4}}\sqrt{T}(\overline{Y}_T - \mu_0) = o_p(1)$

for every $\varepsilon > 0$,

$$\begin{aligned}\lim_{T\to\infty} Pr(|\frac{T^{-\frac{1}{4}}\sqrt{T}(\overline{Y}_T - \mu_0)}{1} - 0| > \varepsilon) = 0\\ \lim_{T\to\infty} Pr(|\frac{(\overline{Y}_T - \mu_0)}{T^{-\frac{1}{4}}} - 0| > \varepsilon) = 0\end{aligned}$$

$$X_T = \overline{Y}_T - \mu_0 = o_p(T^{-\frac{1}{4}})$$

$X_T = \overline{Y}_T - \mu_0$ is of smaller order in probability than $T^{-\frac{1}{4}}$

(c)

$X_T = \overline{Y}_T - \mu_0$ is of smaller order in probability than $T^{-\frac{1}{4}}$

informal explanation:

Using $\overline{Y}_T - \mu_0 \overset{approx}{\sim} N(0, \frac{\sigma_0^2}{T})$

$$\begin{aligned}\frac{\overline{Y}_T - \mu_0}{T^{-\frac{1}{4}}} &\approx T^{\frac{1}{4}} \times N(0, \frac{\sigma_0^2}{T})\\ &= N(0, T^{-\frac{1}{2}}\sigma_0^2)\end{aligned}$$

since $T^{-\frac{1}{2}} \to 0$ as $T \to \infty$, $N(0, T^{-\frac{1}{2}}\sigma_0^2)$ will become a degenerate distribution concentrate onto 0. In other words, $\frac{\overline{Y}_T - \mu_0}{T^{-\frac{1}{4}}} = \frac{X_T}{T^{-\frac{1}{4}}} = o_p(1)$ and X_T is of smaller order in probability than $T^{-\frac{1}{4}}$.

(d)

Given the conditions provided in the question 1 and by the central limit theorem,

$$\frac{\sqrt{T}(\overline{Y}_T - \mu_0)}{\sigma_0} \xrightarrow{d} N(0,1)$$

Now $\hat{\sigma}$ is any consistent estimator of $\hat{\sigma}_0$, which means

$$\hat{\sigma}_0 \xrightarrow{p} \hat{\sigma}$$

By the continuous mapping theorem, if $X_T \xrightarrow{d} X$ and $C_T \xrightarrow{p} C$, then $X_T/C_T \xrightarrow{d} X/C$. Thus,

$$\frac{\sqrt{T}(\overline{Y}_T - \mu_0)}{\hat{\sigma}} \xrightarrow{d} N(0,1)$$

2

(a)

$$lnL_T(\boldsymbol{\theta}) = \frac{1}{T} lnf(\mathbf{Y}|\boldsymbol{\theta})$$

independence

$$= \frac{1}{T} ln \prod_{t=1}^{T} f(y_t|\boldsymbol{\theta})$$

identically distributed

$$= \frac{1}{T} ln \prod_{t=1}^{T} (2\pi)^{-1/2} (\sigma^2)^{-1/2} exp\{-\frac{1}{2\sigma^2}(y_t - \mu)^2\}$$

$$= \frac{1}{T} ln[(2\pi)^{-T/2} (\sigma^2)^{-T/2} \prod_{t=1}^{T} exp\{-\frac{1}{2\sigma^2}(y_t - \mu)^2\}]$$

$$= \frac{1}{T} ln[(2\pi)^{-T/2} (\sigma^2)^{-T/2} exp\{\sum_{t=1}^{T} -\frac{1}{2\sigma^2}(y_t - \mu)^2\}]$$

$$= \frac{1}{T} ln[(2\pi)^{-T/2} (\sigma^2)^{-T/2} exp\{-\frac{1}{2\sigma^2} \sum_{t=1}^{T}(y_t - \mu)^2\}]$$

$$= \frac{1}{T}[ln((2\pi)^{-T/2}) + ln((\sigma^2)^{-T/2}) + ln(exp\{-\frac{1}{2\sigma^2} \sum_{t=1}^{T}(y_t - \mu)^2\})]$$

$$= \frac{1}{T}[ln((2\pi)^{-T/2}) + ln((\sigma^2)^{-T/2}) - \frac{1}{2\sigma^2} \sum_{t=1}^{T}(y_t - \mu)^2]$$

$$= \frac{1}{T}[\frac{-T}{2} ln(2\pi) + \frac{-T}{2} ln(\sigma^2) - \frac{1}{2\sigma^2} \sum_{t=1}^{T}(y_t - \mu)^2]$$

$$= -\frac{1}{2} ln(2\pi) - \frac{1}{2} ln(\sigma^2) - \frac{1}{2\sigma^2} \frac{1}{T} \sum_{t=1}^{T}(y_t - \mu)^2$$

(b)

$$
\begin{aligned}
G_T(\boldsymbol{\theta}) &= \frac{1}{T}\sum_{t=1}^{T} g_t(\boldsymbol{\theta}) \\
&= \frac{1}{T}\sum_{t=1}^{T} \frac{\partial lnf(y_t|\boldsymbol{\theta})}{\partial \boldsymbol{\theta}}
\end{aligned}
$$

identically distributed

$$
\begin{aligned}
&= \frac{1}{T}\sum_{t=1}^{T} \frac{\partial ln((2\pi)^{-1/2}(\sigma^2)^{-1/2}exp\{-\frac{1}{2\sigma^2}(y_t-\mu)^2\})}{\partial \boldsymbol{\theta}} \\
&= \frac{1}{T}\sum_{t=1}^{T} \frac{\partial ln((2\pi)^{-1/2}) + ln((\sigma^2)^{-1/2}) - \frac{1}{2\sigma^2}(y_t-\mu)^2}{\partial \boldsymbol{\theta}} \\
&= \frac{1}{T}\sum_{t=1}^{T} \begin{bmatrix} \frac{\partial ln((2\pi)^{-1/2}) + ln((\sigma^2)^{-1/2}) - \frac{1}{2\sigma^2}(y_t-\mu)^2}{\partial \mu} \\ \frac{\partial ln((2\pi)^{-1/2}) + ln((\sigma^2)^{-1/2}) - \frac{1}{2\sigma^2}(y_t-\mu)^2}{\partial \sigma} \end{bmatrix} \\
&= \frac{1}{T}\sum_{t=1}^{T} \begin{bmatrix} \frac{1}{\sigma^2}(y_t-\mu) \\ -\frac{1}{\sigma} + (y_t-\mu)^2\sigma^{-3} \end{bmatrix}
\end{aligned}
$$

(c)

$$
\begin{aligned}
H_T(\boldsymbol{\theta}) &= \frac{1}{T}\sum_{t=1}^{T} h_t(\boldsymbol{\theta}) \\
&= \frac{1}{T}\sum_{t=1}^{T} \frac{\partial^2 lnf(y_t|\boldsymbol{\theta})}{\partial \boldsymbol{\theta}\partial \boldsymbol{\theta}'} \\
&= \frac{1}{T}\sum_{t=1}^{T} \begin{bmatrix} \frac{\partial^2 lnf(y_t|\boldsymbol{\theta})}{\partial \mu^2} & \frac{\partial^2 lnf(y_t|\boldsymbol{\theta})}{\partial \mu \partial \sigma} \\ \frac{\partial^2 lnf(y_t|\boldsymbol{\theta})}{\partial \sigma \partial \mu} & \frac{\partial^2 lnf(y_t|\boldsymbol{\theta})}{\partial \sigma^2} \end{bmatrix}
\end{aligned}
$$

using the result from part b

$$
= \frac{1}{T}\sum_{t=1}^{T} \begin{bmatrix} -\frac{1}{\sigma^2} & -2(y_t-\mu)\sigma^{-3} \\ -2(y_t-\mu)\sigma^{-3} & \frac{1}{\sigma^2} - 3(y_t-\mu)^2\sigma^{-4} \end{bmatrix}
$$

(d)

To derive the MLE, we set the first order derivative of $lnL_T(\boldsymbol{\theta})$ to $\mathbf{0}$

$$G_T(\boldsymbol{\theta}) = \frac{1}{T}\sum_{t=1}^{T}\begin{bmatrix} \frac{1}{\sigma^2}(y_t-\mu) \\ -\frac{1}{\sigma}+(y_t-\mu)^2\sigma^{-3}\end{bmatrix} = \mathbf{0}$$

$$\begin{bmatrix} \frac{1}{T}\sum_{t=1}^{T}\frac{1}{\sigma^2}(y_t-\mu) \\ \frac{1}{T}\sum_{t=1}^{T}-\frac{1}{\sigma}+(y_t-\mu)^2\sigma^{-3}\end{bmatrix} = \mathbf{0}$$

$$\hat{\mu}_{MLE} = \overline{y} = \frac{1}{T}\sum_{t=1}^{T} y_t$$

$$\hat{\sigma}_{MLE} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(y_t-\overline{y})^2}$$

$$\hat{\boldsymbol{\theta}}_{MLE} = (\hat{\mu}_{MLE}, \hat{\sigma}_{MLE})'$$

We define a non-zero column vector $\boldsymbol{z}$ with real entries a and b

$$\begin{aligned}
\boldsymbol{z}'H_T(\boldsymbol{\theta})\boldsymbol{z} &= \begin{bmatrix} a & b\end{bmatrix}\left(\frac{1}{T}\sum_{t=1}^{T}\begin{bmatrix} -\frac{1}{\sigma^2} & -2(y_t-\mu)\sigma^{-3} \\ -2(y_t-\mu)\sigma^{-3} & \frac{1}{\sigma^2}-3(y_t-\mu)^2\sigma^{-4}\end{bmatrix}\right)\begin{bmatrix} a \\ b\end{bmatrix} \\
&= \begin{bmatrix} a\frac{1}{T}\sum_{t=1}^{T}-\frac{1}{\sigma^2}+b\frac{1}{T}\sum_{t=1}^{T}-2(y_t-\mu)\sigma^{-3} & a\frac{1}{T}\sum_{t=1}^{T}-2(y_t-\mu)\sigma^{-3}+b\frac{1}{T}\sum_{t=1}^{T}\frac{1}{\sigma^2}-3(y_t-\mu)^2\sigma^{-4}\end{bmatrix}\begin{bmatrix} a \\ b\end{bmatrix} \\
&= a^2\frac{1}{T}\sum_{t=1}^{T}-\frac{1}{\sigma^2}+ab\frac{1}{T}\sum_{t=1}^{T}-2(y_t-\mu)\sigma^{-3}+ab\frac{1}{T}\sum_{t=1}^{T}-2(y_t-\mu)\sigma^{-3}+b^2\frac{1}{T}\sum_{t=1}^{T}\frac{1}{\sigma^2}-3(y_t-\mu)^2\sigma^{-4} \\
&= a^2\frac{1}{T}\sum_{t=1}^{T}-\frac{1}{\sigma^2}+2ab\frac{1}{T}\sum_{t=1}^{T}-2(y_t-\mu)\sigma^{-3}+b^2\frac{1}{T}\sum_{t=1}^{T}\frac{1}{\sigma^2}-3(y_t-\mu)^2\sigma^{-4} \\
&= -\frac{a^2}{\sigma^2}+\frac{b^2}{\sigma^2}-\frac{b^2}{T}\sum_{t=1}^{T}3(y_t-\mu)^2\sigma^{-4}-\frac{2ab}{T}\sum_{t=1}^{T}2(y_t-\mu)\sigma^{-3} \\
&= \frac{b^2-a^2}{\sigma^2}-3\frac{b^2}{T}\sigma^{-4}\sum_{t=1}^{T}(y_t-\mu)^2-\frac{4ab}{T}\sigma^{-3}\sum_{t=1}^{T}(y_t-\mu)
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{z}'H_T(\hat{\boldsymbol{\theta}}_{MLE})\boldsymbol{z} &= \frac{b^2-a^2}{\hat{\sigma}^2_{MLE}}-3\frac{b^2}{T}\hat{\sigma}^{-4}_{MLE}\sum_{t=1}^{T}(y_t-\hat{\mu}_{MLE})^2-\frac{4ab}{T}\hat{\sigma}^{-3}_{MLE}\sum_{t=1}^{T}(y_t-\hat{\mu}_{MLE}) \\
&= \frac{b^2-a^2}{\hat{\sigma}^2_{MLE}}-3\frac{b^2}{T}\hat{\sigma}^{-4}_{MLE}T\hat{\sigma}^2_{MLE}-0 \\
&= \frac{-2b^2-a^2}{\hat{\sigma}^2_{MLE}}
\end{aligned}$$

Since $-2b^2-a^2<0$ and $\hat{\sigma}^2_{MLE}>0$,

$$\frac{-2b^2-a^2}{\hat{\sigma}^2_{MLE}} < 0$$

$H_T(\hat{\boldsymbol{\theta}}_{MLE})$ is a negative definite matrix. The second-order condition for a maximum holds.

(e)

Using the equation in part a, and replace σ^2 with $\frac{1}{\sigma^{-2}}$

$$lnL_T(\boldsymbol{\eta}) = -\frac{1}{2}ln(2\pi) - \frac{1}{2}ln(\frac{1}{\sigma^{-2}}) - \frac{1}{2\frac{1}{\sigma^{-2}}}\frac{1}{T}\sum_{t=1}^{T}(y_t-\mu)^2$$

$$\begin{aligned}
G_T(\boldsymbol{\eta}) &= \frac{1}{T}\sum_{t=1}^{T} g_t(\boldsymbol{\eta}) \\
&= \frac{1}{T}\sum_{t=1}^{T}\frac{\partial lnf(y_t|\boldsymbol{\eta})}{\partial \boldsymbol{\eta}}
\end{aligned}$$

identically distributed

$$\begin{aligned}
&= \frac{1}{T}\sum_{t=1}^{T}\frac{\partial ln((2\pi)^{-1/2}(\frac{1}{\sigma^{-2}})^{-1/2}exp\{-\frac{1}{2\frac{1}{\sigma^{-2}}}(y_t-\mu)^2\})}{\partial \boldsymbol{\eta}} \\
&= \frac{1}{T}\sum_{t=1}^{T}\frac{\partial ln((2\pi)^{-1/2}) + ln((\frac{1}{\sigma^{-2}})^{-1/2}) - \frac{1}{2\frac{1}{\sigma^{-2}}}(y_t-\mu)^2}{\partial \boldsymbol{\eta}} \\
&= \frac{1}{T}\sum_{t=1}^{T}\begin{bmatrix} \frac{\partial ln((2\pi)^{-1/2}) + ln((\frac{1}{\sigma^{-2}})^{-1/2}) - \frac{1}{2\frac{1}{\sigma^{-2}}}(y_t-\mu)^2}{\partial \mu} \\ \frac{\partial ln((2\pi)^{-1/2}) + ln((\frac{1}{\sigma^{-2}})^{-1/2}) - \frac{1}{2\frac{1}{\sigma^{-2}}}(y_t-\mu)^2}{\partial \sigma^{-2}} \end{bmatrix} \\
&= \frac{1}{T}\sum_{t=1}^{T}\begin{bmatrix} \frac{1}{\sigma^2}(y_t-\mu) \\ \frac{1}{2\sigma^{-2}} - \frac{1}{2}(y_t-\mu)^2 \end{bmatrix}
\end{aligned}$$

$$H_T(\boldsymbol{\eta}) = \begin{bmatrix} -\frac{1}{\sigma^2} & y_t-\mu \\ y_t-\mu & -\frac{1}{2}(\sigma^{-2})^{-2} \end{bmatrix}$$

Set $G_T(\boldsymbol{\eta}) = \mathbf{0}$,

$$\hat{\mu}_{MLE} = \overline{y} = \frac{1}{T}\sum_{t=1}^{T} y_t$$

$$\widehat{\sigma^{-2}}_{MLE} = [\frac{1}{T}\sum_{t=1}^{T}(y_t-\overline{y})^2]^{-1}$$

$$\hat{\boldsymbol{\eta}}_{MLE} = (\hat{\mu}_{MLE}, \widehat{\sigma^{-2}}_{MLE})'$$

We define a non-zero column vector $\boldsymbol{z}$ with real entries a and b

$$
\begin{aligned}
\boldsymbol{z}'H_T(\boldsymbol{\theta})\boldsymbol{z} &= \begin{bmatrix} a & b \end{bmatrix} \left(\frac{1}{T}\sum_{t=1}^{T}\begin{bmatrix} -\frac{1}{\sigma^2} & y_t-\mu \\ y_t-\mu & -\frac{1}{2}(\sigma^{-2})^{-2} \end{bmatrix}\right)\begin{bmatrix} a \\ b \end{bmatrix} \\
&= \frac{a^2}{T}\sum_{t=1}^{T} -\frac{1}{\sigma^2} + 2\frac{ab}{T}\sum_{t=1}^{T}(y_t-\mu) + \frac{b^2}{T}\sum_{t=1}^{T} -\frac{1}{2}(\sigma^{-2})^2 \\
&= -\frac{a^2}{\sigma^2} + 2\frac{ab}{T}\sum_{t=1}^{T}(y_t-\mu) - \frac{b^2}{2}(\sigma^{-2})^2
\end{aligned}
$$

$$
\begin{aligned}
\boldsymbol{z}'H_T(\boldsymbol{\theta}_{MLE})\boldsymbol{z} &= -a^2\widehat{\sigma^{-2}}_{MLE} + 2\frac{ab}{T}\sum_{t=1}^{T}(y_t-\hat{\mu}_{MLE}) - \frac{b^2}{2}(\widehat{\sigma^{-2}}_{MLE})^2 \\
&= -a^2\widehat{\sigma^{-2}}_{MLE} - \frac{b^2}{2}(\widehat{\sigma^{-2}}_{MLE})^2
\end{aligned}
$$

Since $\widehat{\sigma^{-2}}_{MLE} > 0$, $(\widehat{\sigma^{-2}}_{MLE})^2 > 0$ $a^2 > 0$ and $\frac{b^2}{2} > 0$, so

$$
-a^2\widehat{\sigma^{-2}}_{MLE} - \frac{b^2}{2}(\widehat{\sigma^{-2}}_{MLE})^2 < 0
$$

$H_T(\hat{\boldsymbol{\eta}}_{MLE})$ is a negative definite matrix. The second-order condition for a maximum holds. The second-order condition for a maximum holds.

Meanwhile,

$$
\widehat{\sigma^{-2}}_{MLE} = \left(\sqrt{\frac{1}{T}\sum_{t=1}^{T}(y_t-\overline{y})^2}\right)^{-2} = (\hat{\sigma}_{MLE})^{-2} = C(\hat{\sigma}_{MLE})
$$

and

$$
\hat{\mu}_{MLE} = \hat{\mu}_{MLE} = C(\hat{\mu}_{MLE})
$$

.

We also know

$C(\sigma_0) = \sigma_0^{-2}$ and $C(\mu_0) = \mu_0$

$\Longrightarrow$ The functions apply to the true parameters are the same as the functions we obtain from the MLE. Thus,

$$
\hat{\boldsymbol{\eta}}_{MLE} = C(\hat{\boldsymbol{\theta}}_{MLE})
$$

if $\boldsymbol{\eta}_0 = C(\boldsymbol{\theta}_0)$ and $\hat{\boldsymbol{\theta}}_{MLE}$ is the MLE of $\boldsymbol{\theta}_0$.