AI 1103 - Challenging Problem 11

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https://github.com/rohanthota/Challenging_problem/main.tex

1 Problem

(UGC/MATH 2018 (June set-a)-Q.106) Let $X_{i i\geq 1}$ be a sequence of i.i.d. random variables with $E(X_i) = 0$ and $V(X_i) = 1$. Which of the following are true?

1) $\frac{1}{n}\sum_{i=1}^{n} X_i^2 \to 0$ in probability
2) $\frac{1}{n^{3/4}}\sum_{i=1}^{n} X_i \to 0$ in probability
3) $\frac{1}{n^{1/2}}\sum_{i=1}^{n} X_i \to 0$ in probability
4) $\frac{1}{n}\sum_{i=1}^{n} X_i^2 \to 1$ in probability

2 Solution

Definition 1. *(Convergence in distribution)*
A sequence of random variables Y, Y_1, $Y_2\dots$ converges in distribution to a random variable Y, if

$$\lim_{n\to\infty} F_{X_n}(a) = F_X(a)\ \forall a \in \mathbb{R}. \tag{2.0.1}$$

Definition 2. *(Convergence in probability)*
A sequence of random variables Y, Y_1, $Y_2\dots$ is said to converge in probability to Y, if

$$\lim_{n\to\infty} \Pr\left(|Y_n - Y| > \epsilon\right) = 0\ \forall \epsilon > 0. \tag{2.0.2}$$

Lemma 2.1. *If $Y_n \to Y$ in probability, $Y_n \to Y$ in distribution.*

Lemma 2.2. *(Strong Law of Large Numbers)*
Let X_1, X_2, $\dots X_n$ be i.i.d. random variables with expected value $E(X_i) = \mu < \infty$, then,

$$\lim_{n\to\infty} \Pr\left(\left|\frac{1}{n}\sum_{i=1}^{n} X_i - \mu\right| \geq \epsilon\right) = 0 \tag{2.0.3}$$

Or, $\frac{1}{n}\sum_{i=1}^{n} X_i$ converges in probability to μ.

1)

Lemma 2.3. *If X_i is a sequence of i.i.d. random variables, it follows that X_i^2 is also a sequence of i.i.d. random variables.*

Proof. X_i is a sequence of i.i.d. random variables, which means it satisfies the following conditions.

$$F_{X_1}(x) = F_{X_2}(x) = \dots = F_{X_n}(x) = F_X(x) \tag{2.0.4}$$

$$F_{X_1,\dots X_n}(x_1 \dots x_n) = F_X(x_1)F_X(x_2)\dots F_X(x_n) \tag{2.0.5}$$

where $F_X(x)$ is the c.d.f. of X_i.
Let $Y_i = X_i^2$. We try to prove conditions (2.0.4) and (2.0.5) for Y_i

a) For $y \geq 0$,

$$F_{Y_i}(y) = \Pr\left(Y_i \leq y\right) \tag{2.0.6}$$

$$\implies F_{Y_i}(y) = \Pr\left(X_i^2 \leq y\right) \tag{2.0.7}$$

$$\implies F_{Y_i}(y) = \Pr\left(-\sqrt{y} \leq X_i \leq \sqrt{y}\right) \tag{2.0.8}$$

$$\implies F_{Y_i}(y) = \Pr\left(X_i \leq \sqrt{y}\right) - \Pr\left(X_i \leq -\sqrt{y}\right) \tag{2.0.9}$$

$$\implies F_{Y_i}(y) = F_{X_i}(\sqrt{y}) - F_{X_i}(-\sqrt{y}) \tag{2.0.10}$$

Using (2.0.4) for $\{X_i\}$,

$$F_{Y_i}(y) = F_X(\sqrt{y}) - F_X(-\sqrt{y}) \tag{2.0.11}$$

From (2.0.11),

$$F_{Y_1}(y) = F_{Y_2}(y) = \dots = F_{Y_n}(y) = F_Y(y) \tag{2.0.12}$$

where $F_Y(y)$ is the c.d.f. of $Y_i = X_i^2$.

b) Now, for $y_i \geq 0$, consider

$$\begin{aligned} &F_{Y_1,Y_2,\dots,Y_n}(y_1, y_2, \dots, y_n) \\ &= \Pr\left(Y_1 \leq y_1, Y_2 \leq y_2, \dots, Y_n \leq y_n\right) \end{aligned} \tag{2.0.13}$$

$$= \Pr\left(X_1^2 \le y_1, X_2^2 \le y_2, \dots, X_n^2 \le y_n\right) \tag{2.0.14}$$

$$= \Pr\left(-\sqrt{y_1} \le X_1 \le \sqrt{y_1}, -\sqrt{y_2} \le X_2 \le \sqrt{y_2}, \dots, -\sqrt{y_n} \le X_n \le \sqrt{y_n}\right) \tag{2.0.15}$$

Since $X_1, X_2, \dots, X_n$ are independent,

$$F_{Y_1,Y_2,\dots,Y_n}(y_1, y_2, \dots, y_n) = \Pr\left(-\sqrt{y_1} \le X_1 \le \sqrt{y_1}\right)\Pr\left(-\sqrt{y_2} \le X_2 \le \sqrt{y_2}\right) \dots \Pr\left(-\sqrt{y_n} \le X_n \le \sqrt{y_n}\right) \tag{2.0.16}$$

From (2.0.8) and (2.0.12),

$$F_{Y_1,Y_2,\dots,Y_n}(y_1, y_2, \dots, y_n) = F_{Y_1}(y_1)F_{Y_2}(y_2)\dots F_{Y_n}(y_n) \tag{2.0.17}$$

$$= F_Y(y_1)F_Y(y_2)\dots F_Y(y_n) \tag{2.0.18}$$

So,

$$F_{Y_1,Y_2,\dots,Y_n}(y_1, y_2, \dots, y_n) = F_Y(y_1)F_Y(y_1)\dots F_Y(y_n) \tag{2.0.19}$$

By (2.0.12) and (2.0.19), $\{Y_i\} = \{X_i^2\}$ must also be a sequence of i.i.d. random variables. □

We know,

$$E(X_i^2) = V(X_i) + (E(X_i))^2 \tag{2.0.20}$$

Putting given values, we get,

$$E(X_i^2) = 1 \tag{2.0.21}$$

From 2.2, $\frac{1}{n}\sum_{i=1}^{n} X_i^2$ converges in probability to $E(X_i^2) = 1$.

Therefore, option 1 is incorrect.

2) Let us define $Y_n = \frac{1}{n^{3/4}}\sum_{i=1}^{n} X_i$.
Then,

$$E(Y_n) = \frac{1}{n^{3/4}} E\left(\sum_{i=1}^{n} X_i\right) \tag{2.0.22}$$

$$\implies E(Y_n) = 0 \tag{2.0.23}$$

Since $E(X_i) = 0$

Lemma 2.4. *If $X_1, X_2, \dots X_n$ are independent random variables,*

$$V\left(\sum_{i=1}^{n} X_i\right) = V(X_1) + V(X_2) + \dots + V(X_n) \tag{2.0.24}$$

Here,

$$V(Y_n) = V\left(\frac{1}{n^{3/4}}\sum_{i=1}^{n} X_i\right) \tag{2.0.25}$$

$$V(Y_n) = \frac{1}{n^{3/2}} V\left(\sum_{i=1}^{n} X_i\right) \tag{2.0.26}$$

$$\implies V(Y_n) = \frac{1}{n^{3/2}} \times n = \frac{1}{n^{1/2}} \tag{2.0.27}$$

Since $V(X_i) = 1$

Lemma 2.5. *(Chebyshev's Inequality)*
Let the random variable X have a finite mean μ and a finite variance σ^2. For every $\epsilon > 0$,

$$\Pr\left(|X - \mu| \ge \epsilon\right) \le \frac{\sigma^2}{\epsilon^2} \tag{2.0.28}$$

For Y_n,

$$\Pr\left(|Y_n - E(Y_n)| \ge \epsilon\right) \le \frac{V(Y_n)}{\epsilon^2} \tag{2.0.29}$$

$$\implies \lim_{n\to\infty} \Pr\left(|Y_n - 0| \ge \epsilon\right) \le \lim_{n\to\infty} \frac{1}{n^{1/2}\epsilon^2} \,(= 0) \tag{2.0.30}$$

$$\implies \lim_{n\to\infty} \Pr\left(\left|\frac{1}{n^{3/4}}\sum_{i=1}^{n} X_i - 0\right| \ge \epsilon\right) = 0 \tag{2.0.31}$$

So, $\frac{1}{n^{3/4}}\sum_{i=1}^{n} X_i \to 0$ in probability.
Thus, option 2 is correct.

3) The option states that $\frac{1}{n^{1/2}}\sum_{i=1}^{n} X_i \to 0$ in probability. This statement implies that $\frac{1}{n^{1/2}}\sum_{i=1}^{n} X_i \to 0$ in distribution, from 2.1.

Lemma 2.6. *(Central Limit Theorem)*
Let X_1, X_2, $\dots X_n$ be i.i.d. random variables with expected value $E(X_i) = \mu < \infty$ and $0 < V(X_i) = \sigma^2 < \infty$. Then the random variable

$$Z_n = \frac{\bar{x} - \mu}{\frac{\sigma}{\sqrt{n}}} = \frac{\sum_{i=1}^{n} X_i - n\mu}{\sqrt{n}\sigma} \tag{2.0.32}$$

converges in distribution to the standard normal random variable as n goes to infinity, that is

$$\lim_{n\to\infty} \Pr\left(Z_n \le a\right) = \Phi(a) \;\forall a \in \mathbb{R}. \tag{2.0.33}$$

where $\Phi(a)$ is the standard normal CDF.

Writing the random variable Z_n for $\{X_i\}$ where

$\mu = 0$ and $\sigma = 1$,

$$Z_n = \frac{1}{n^{1/2}} \sum_{i=1}^{n} X_i \tag{2.0.34}$$

where,

$$Z_n \to Z, \text{where, } Z \sim N(0, 1) \tag{2.0.35}$$

The above result doesn't match the option's statement. Therefore, option 3 is incorrect.

4) As proved in option (1), $\frac{1}{n} \sum_{i=1}^{n} X_i^2 \to 1$ in probability. So option 4 is correct.

Therefore, options 2 and 4 are correct.