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Jiamin JIAN

Exercise 1:

Let $E := [0,1] - S_{\mathbb{Q}} = [0,1]\bigcap(S_{\mathbb{Q}})^c$ where $S_{\mathbb{Q}} := \{x \in [0,1] | x = \frac{\sqrt{p}}{q} \text{ for some } p, q \in \mathbb{Z}^+\}$. Prove or disprove: There exists a closed, uncountable subset $F \subset E$.

Solution:

This proposition is true. Since $S_{\mathbb{Q}}$ is a countable set and it is equivalent with the positive integers in the interval $[0,1]$, we can enumerate the set $S_{\mathbb{Q}}$ as $\{a_n | n \in \mathbb{N}\}$. And then we consider the union $\bigcup_{n=1}^{+\infty}(a_n - \frac{1}{8^n}, a_n + \frac{1}{8^n})$, it is an open set, we denote it as A, then $A = \bigcup_{n=1}^{+\infty}(a_n - \frac{1}{8^n}, a_n + \frac{1}{8^n})$. We introduce the set $A^* = A\bigcap[0,1]$, then $A^* \subset [0,1]$ and $S_{\mathbb{Q}} \subset A^*$, and we have $(A^*)^c \subset (S_{\mathbb{Q}})^c$. Then we know that $[0,1]\bigcap(A^*)^c \subset E$.

Since A^* is an open set, then $[0,1]\bigcap(A^*)^c$ is a closed set. We denote $F = [0,1]\bigcap(A^*)^c$, since the measure of set A is

$$m(A) = 2\sum_{n=1}^{+\infty}\frac{1}{8^n} = \frac{2}{7},$$

then $m(A^*) \leq \frac{2}{7}$. So, we have $m(F) \geq \frac{5}{7} > 0$, then the set F is uncountable. Since $F \subset E$ and it is both closed and uncountable, then the proposition is true.

Exercise 2:

For x in $[-1,1]$ set $P_n(x) = c_n(1-x^2)^n$ where c_n is such that $\int_{-1}^1 P_n = 1$.

(i) Show that there is a positive constant C such that $c_n \leq C\sqrt{n}$.

(ii) Let f be a real valued continuous function on $[0,1]$ such that $f(0) = f(1) = 0$. Set for x in $[0,1]$

$$f_n(x) = \int_0^1 P_n(x-t)f(t)\,dt$$

Show that f_n is uniformly convergence to f.

(iii) Let g be in $L^1((0,1))$. Defining $g_n(x) = \int_0^1 P_n(x-t)g(t)\,dt$, is g_n uniformly convergence to g in $(0,1)$? Does g_n converge to g in $L^1((0,1))$?

Solution:

(i) Method 1:

Since $\int_{-1}^1 c_n(1-x^2)^n\,dx = 1$, then we have

$$c_n = \frac{1}{2\int_0^1(1-x^2)^n\,dx}.$$

Next we need to find a lower bound of the integral term $\int_0^1 (1-x^2)^n\,dx$. Since for $n>1$,

$$\begin{aligned}\int_0^1 (1-x^2)^n\,dx &\geq \int_0^{\frac{1}{\sqrt{n}}} (1-x^2)^n\,dx\\ &\geq \frac{1}{\sqrt{n}}(1-\frac{1}{n})^n,\end{aligned}$$

then we have $c_n \leq \frac{\sqrt{n}}{2(1-\frac{1}{n})^n}$. We just need to find a lower bound of $(1-\frac{1}{n})^n$. Since $(1-\frac{1}{n})^n = 1 - C_n^1\frac{1}{n} + C_n^2\frac{1}{n^2} + \cdots + (-\frac{1}{n})^n > \frac{1}{3} - \frac{2}{6n^2} > \frac{1}{4}$ as $n>1$, then we set $C=2$, we have $c_n \leq C\sqrt{n}$ for $n>1$. For $n=1$, we get $c_1 = \frac{3}{4} < 2$, then when $C=2$, we have $c_n \leq C\sqrt{n}$ holds.

Method 2:

We change the element and define $x=\sin y$, then we have $\int_0^{\frac{\pi}{2}} c_n \cos^{2n+1} y\,dy = \frac{1}{2}$. Since

$$\int_0^{\frac{\pi}{2}} \cos^{2n+1} y\,dy = 2n\int_0^{\frac{\pi}{2}} \cos^{2n-1} y\,dy - 2n\int_0^{\frac{\pi}{2}} \cos^{2n+1} y\,dy,$$

we denote $I_{2n+1} = \int_0^{\frac{\pi}{2}} \cos^{2n+1} y\,dy$, then we have $(2n+1)I_{2n+1} = 2nI_{2n-1}$. Since $I_1 = \int_0^{\frac{\pi}{2}} \cos y\,dy = 1$, we have $\int_0^{\frac{\pi}{2}} \cos^{2n+1} y\,dy = \frac{(2n)!!}{(2n+1)!!}$. And since

$$\begin{aligned}\frac{(2n)!!}{(2n+1)!!} &= \frac{2n(2n-2)\cdots 2}{(2n+1)(2n-1)\cdots 3}\\ &\geq \frac{\sqrt{2n+1}\sqrt{2n-1}\sqrt{2n-1}\sqrt{2n-3}\cdots\sqrt{3}\sqrt{1}}{(2n+1)(2n-1)\cdots 3}\\ &= \frac{1}{\sqrt{2n+1}},\end{aligned}$$

then we have $c_n \leq \frac{\sqrt{2n+1}}{2}$. We set $C=1$, then we have $c_n \leq C\sqrt{n}$.

(ii) Firstly we extend $f(x)$ to a function from $\mathbb{R}$ to $\mathbb{R}$ by zero. Then we have

$$f_n(x) = \int_0^1 P_n(x-t)f(t)\,dt = \int_{\mathbb{R}} P_n(x-t)f(t)\,dt,$$

then we change the element as $x-t=y$, we have

$$f_n(x) = \int_{\mathbb{R}} P_n(y)f(x-y)\,dy.$$

Then we know that

$$\begin{aligned}|f_n(x)-f(x)| &= \Big|\int_{\mathbb{R}} P_n(y)f(x-y)\,dy - \int_{-1}^1 P_n(y)f(x)\,dy\Big|\\ &= \Big|\int_{-1}^1 P_n(y)(f(x-y)-f(x))\,dy + \int_{([-1,1])^c} P_n(y)f(x-y)\,dy\Big|\\ &\leq \int_{-1}^1 P_n(y)|(f(x-y)-f(x))|\,dy + \int_{([-1,1])^c} |P_n(y)f(x-y)|\,dy.\end{aligned}$$

Since when $x \in [0,1]$ and $y \in ([-1,1])^c$, we have $x-y>1$ or $x-y<0$, then we have $f(x-y)=0$, so we have

$$|f_n(x)-f(x)| \leq \int_{-1}^{1} P_n(y)|(f(x-y)-f(x))|\,dy.$$

And by the definition of continuous, we have $\forall \epsilon > 0$, there $\exists \delta$, when $|x-y-x|<\delta$, we have $|f(x-y)-f(x)|<\epsilon$. We denote $S=[-1,1]\bigcap[-\delta,\delta]$, since $f(x)$ is continuous in $\mathbb{R}$, we denote $\sup_{x\in[0,1]} f(x) = M$, then we have $M<+\infty$ and

$$\begin{aligned}
|f_n(x)-f(x)| &\leq \int_{-\delta}^{\delta} P_n(y)|(f(x-y)-f(x))|\,dy + \int_S P_n(y)|(f(x-y)-f(x))|\,dy \\
&\leq \epsilon \int_{-\delta}^{\delta} P_n(y)\,dy + 2M\int_S P_n(y)\,dy \\
&\leq \epsilon + 2M\int_S c_n(1-y^2)^n\,dy \\
&\leq \epsilon + 4MC\sqrt{n}\int_{\delta}^{1}(1-y^2)^n\,dy \\
&\leq \epsilon + 4MC\sqrt{n}(1-\delta)(1-\delta^2)^n.
\end{aligned}$$

Since $\lim_{n\to+\infty} 4MC\sqrt{n}(1-\delta)(1-\delta^2)^n = 0$, then we can say that there exists a $N\in\mathbb{N}$, when $n>N$, we have $4MC\sqrt{n}(1-\delta)(1-\delta^2)^n<\epsilon$. Overall, we know that $\forall x\in[0,1], \forall \epsilon > 0$, there exists a $N\in\mathbb{N}$, when $n>N$, we have $|f_n(x)-f(x)|<2\epsilon$, so that f_n is uniformly converges to f.

(iii) Firstly, the $g_n(x)$ is not uniformly convergent to g in $(0,1)$, we can give an counter example as following. We define

$$g(x)=\begin{cases} 1, & x=\frac{1}{2} \\ 0, & x\in(0,\frac{1}{2})\bigcup(\frac{1}{2},1), \end{cases}$$

obviously $g(x)$ is not continuous in $(0,1)$, but we have $g_n(x)=\int_0^1 P_n(x-t)g(t)\,dt = 0, \forall x\in(0,1)$. Then $g_n(x)$ is continuous in $[0,1]$. Since $g(x)$ is not continuous in $(0,1)$, we can say that $g_n(x)$ is not uniformly convergent to $g(x)$ in $(0,1)$.

Secondly, we can show that $g_n(x)$ convergent to $g(x)$ in $L^1((0,1))$. Since continuous function is dense in L^1 space, then for all $\epsilon>0$, there exist a continuous function $f(x)$, such that $\|f-g\|_1<\epsilon$. We define the $f_n(x)$ as the section (ii), then we have

$$\|g-g_n\|_1 \leq \|g-f\|_1 + \|f-f_n\|_1 + \|f_n-g_n\|_1.$$

Since f_n is uniformly converges to f, for all $\epsilon>0$, there exists a $N in \mathbb{N}$, when $n>N$, we have $\|f-f_n\|_1<\epsilon$. And for the same ϵ, by the property that continuous function is dense in L^1 space, we have $\|f-g\|_1 < \epsilon$. Next we verify that $\|f_n - g_n\|_1 < \epsilon$. Since

$$\begin{aligned}\|f_n - g_n\|_1 &= \int_0^1 \Big| \int_0^1 P_n(x-t)g(t) - \int_0^1 P_n(x-t)f(t)\,dt \Big| dx \\ &= \int_0^1 \Big| \int_0^1 P_n(x-t)(g(t)-f(t))\,dt \Big| dx \\ &\le \int_0^1 \int_0^1 P_n(x-t)|g(t)-f(t)|\,dtdx,\end{aligned}$$

and $P_n(x-t)$ is continuous for $t \in [0,1]$, then we can find the upper bound for $P_n(x-t)$, we denote it as C, then we have

$$\begin{aligned}\|f_n - g_n\|_1 &\le \int_0^1 \int_0^1 P_n(x-t)|g(t)-f(t)|\,dtdx \\ &\le C\int_0^1 \int_0^1 |g(t)-f(t)|\,dtdx \\ &= C\int_0^1 |g(t)-f(t)|\,dt \\ &= C\|g-f\|_1.\end{aligned}$$

Since $\|g-f\|_1 < \epsilon$, we have $\|g-g_n\|_1 < (2+\frac{1}{C})\epsilon$ for all $\epsilon > 0$. So, we know that $g_n(x)$ convergent to $g(x)$ in $L^1((0,1))$.

Exercise 3:

Give an example of $f_n, f : \mathbb{R} \mapsto [0,\infty)$ such that $f_n \in L^1(\mathbb{R})$ for every $n \in \mathbb{N}$, $f \in L^2(\mathbb{R})$, $f_n \le f$ for every $n \in \mathbb{N}$, $f_n \to 0$ a.e., and $\int f_n \nrightarrow 0$.

Solution:

We define the $f(x) = \frac{1}{x}\mathbb{I}_{[1,+\infty)}$ and $f_n(x) = \frac{1}{x}\mathbb{I}_{[n,n^2]}$. For a fixed n, we have

$$\int_{\mathbb{R}} |f_n(x)|\,dx = \int_n^{n^2} \frac{1}{x}\,dx = \ln n,$$

so we have $f_n \in L^1(\mathbb{R})$ for every $n \in \mathbb{N}$. And since

$$\int_{\mathbb{R}} |f(x)|^2\,dx = \int_1^{+\infty} \frac{1}{x^2}\,dx = 1,$$

so we know that $f \in L^2(\mathbb{R})$. Since for all n, f_n is just a part of f and $f > 0$, then we have $f_n \le f$ for every $n \in \mathbb{N}$. When $n \to +\infty$, we have $f_n(x) \le \frac{1}{n}$, so that $f_n \to 0$ almost everywhere. And we calculate the integral of f_n, we have

$$\int_{\mathbb{R}} f_n(x)\,dx = \int_n^{n^2} \frac{1}{x}\,dx = \ln n,$$

when $n \to +\infty$, $\ln n \to +\infty$, so we can get $\int f_n \nrightarrow 0$.