

Introduction to Analysis II

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Introduction & Notice

- 7, 8장 나가고 중간고사, 11장 나가고 기말고사
- 연습 시간이 있는 수업 (목 6:30 ~ 8:20)¹
- 오늘 연습 시간: 지난학기 배운 내용 중 필요한 내용 복습

¹가능하면 1시간 반 안에 끝내라고 하심 ㅋㅋ

Chapter 7

Sequences and Series of Functions

September 1st, 2022

함수들을 각각 보는 것보다 **함수들의 공간을 이해**하는 것이 해석학의 핵심이다! 공간을 이해해야 미분방정식도 풀고 실제 현실의 문제들을 풀 수 있는 것입니다.

\mathbb{R}^n 을 단순히 좌표들의 모임으로 보는 것이 아니라, 거리 구조를 주고 열린/닫힌 집합과 같은 위상 구조를 줬었습니다. 이 전에 했던게 **수열의 수렴과 발산, 코시 수열**이죠. 이런 것들을 바탕으로 공간의 위상적 성질을 조금 더 효율적으로 공부할 수 있었습니다.

즉, 어떤 공간을 배우기 위해서는 수열의 수렴이나 발산을 배워야 합니다. **따라서 우리는 함수들의 공간을 공부하기 위해 우선 함수열을 공부합니다.**

Suppose E is a set¹, and let $f_n : E \rightarrow \mathbb{C}$ for all $n \in \mathbb{N}$. Then

$$(f_n)_{n=1}^{\infty}$$

is a sequence of (complex-valued) function.

수열을 공부했으니 수열의 **수렴**을 정의해야 할 것입니다.

Definition 7.1 (Pointwise Convergence) $(f_n)_{n=1}^{\infty}$ converges **pointwise** on E , if for each $x \in E$ the sequence $(f_n(x))_{n=1}^{\infty}$ converges in \mathbb{C} .

In other words, for each $x \in E$, there exists $a_x \in \mathbb{C}$ and

$$\forall \epsilon > 0, \exists N_x \in \mathbb{N} \text{ such that } n \geq N_x \implies |f_n(x) - a_x| < \epsilon.$$

¹사실은 *metric space* 이다.

Definition. If (f_n) converges pointwise, we can define a function f by

$$f(x) = \lim_{n \rightarrow \infty} f_n(x) \quad (x \in E)$$

We say that

- f is the *limit* or *limit function* of f_n .
- (f_n) to f pointwise on E .

Definition. If $\sum f_n(x)$ converges (pointwise) for every $x \in E$, we can define

$$f(x) = \sum_{n=1}^{\infty} f_n(x) \quad (x \in E)$$

and the function f is called the *sum* of the series $\sum f_n$.

Recall. $f : (E, d) \rightarrow \mathbb{C}$ is continuous on $E \iff f$ is continuous at all $x \in E$.

Recall. (Theorem 4.6) If $p \in E$ and p is a limit point of E ,

$$f \text{ is continuous at } p \iff \lim_{x \rightarrow p} f(x) = f(p)$$

Question. Suppose (f_n) is a sequence of functions. Does the limit function or the sum of the series preserve important properties?

- (1) If f_n is continuous, is f continuous?
- (2) If f_n is differentiable/integrable, is f differentiable/integrable?

For (1), the question is equivalent to the following:

If p is a limit point, does the following hold?

$$\lim_{x \rightarrow p} \lim_{n \rightarrow \infty} f_n(x) \stackrel{?}{=} \lim_{n \rightarrow \infty} \lim_{x \rightarrow p} f_n(x)$$

And the answer is **No**.

실수열이 주어졌을 때, 극한을 계산하여 극한값이 실수라는 것은 굉장히 중요한 것입니다. 우리가 **연속함수열**의 수렴을 정의할 때, 극한이 되는 함수 또한 **연속**이 되기를 기대하는 것은 굉장히 자연스러운 일입니다. 하지만 점별수렴하는 연속함수열의 극한은 연속이 아닐 수 있습니다. 즉, 점별수렴은 연속함수공간에서의 '수렴'으로 정의하기에는 부족합니다.

Example 7.2 Suppose $a_{m,n} = \frac{m}{m+n}$ for $m, n \in \mathbb{N}$. We see that

$$\lim_{n \rightarrow \infty} \lim_{m \rightarrow \infty} a_{m,n} = 1 \neq 0 = \lim_{m \rightarrow \infty} \lim_{n \rightarrow \infty} a_{m,n}$$

Example. Define

$$f_n(x) = \begin{cases} 0 & (\frac{1}{n} \leq x \leq 1) \\ -nx + 1 & (0 \leq x < \frac{1}{n}) \end{cases}$$

then we can easily see that

$$f(x) = \lim_{n \rightarrow \infty} f_n(x) = \begin{cases} 0 & (0 < x \leq 1) \\ 1 & (x = 0) \end{cases}$$

Thus f is not continuous at $x = 0$.

Example. Define $f_n : \mathbb{R} \rightarrow \mathbb{R}$ as

$$f_n(x) = \frac{x^2}{(1+x^2)^n} \quad (n = 0, 1, 2, \dots)$$

by direct calculation,

$$f(x) = \sum_{n=0}^{\infty} f_n(x) = \sum_{n=0}^{\infty} \frac{x^2}{(1+x^2)^n} = 1 + x^2 \quad (x \neq 0)$$

since this is a geometric series when $x \neq 0$. If $x = 0$, $f(x) = 0$ and f is not continuous.

Does the limit function preserve Riemann integrability?

Example. For $m = 1, 2, \dots$, define

$$f_m(x) = \lim_{n \rightarrow \infty} (\cos m! \pi x)^{2n} = \begin{cases} 1 & (m!x \in \mathbb{Z}) \\ 0 & (m!x \notin \mathbb{Z}) \end{cases}$$

We see that $f_m(x)$ is Riemann integrable. However,

Claim.

$$f(x) = \lim_{m \rightarrow \infty} f_m(x) = \begin{cases} 1 & (x \in \mathbb{Q}) \\ 0 & (x \in \mathbb{R} \setminus \mathbb{Q}) \end{cases}$$

and $f(x)$ is nowhere continuous thus not Riemann integrable.

Proof. Suppose $x = p/q \in \mathbb{Q}$. ($p, q \in \mathbb{Z}$) If we take $m \geq q$, we see that $m!x \in \mathbb{Z}$. Thus $f_m(x) = 1$. If $x \notin \mathbb{Q}$, $m!x$ can never be in \mathbb{Z} and $f_m(x) = 0$.

Question. Uniform continuity를 할 때 uniform이 어디서 나오죠? 해석학에서 그 점에서 뭐가 성립한다, 그러면 그 점과 그 근방에서만 확인하면 됐었죠. Continuity는 local property죠. 그런데 uniform continuity는 전체가 다 uniform하게 성립한다는 의미입니다.

Recall. $f : (X, d) \rightarrow (Y, d)$ is uniformly continuous on X ² if

$$\forall \epsilon > 0, \exists \delta > 0 \text{ such that } d_X(p, q) < \delta \implies d_Y(f(p), f(q)) < \epsilon$$

즉, 모든 점에서 똑같이 잡을 수 있다!

Recall. (Theorem 4.19) If X is compact and f is continuous on X , then f is uniformly continuous on X .³

이제부터 나오는 uniform convergence는 sequence에 관한 것입니다!

Definition 7.7 (Uniform Convergence) Suppose $f_n : E \rightarrow \mathbb{C}$ is a sequence of functions. $(f_n)_{n=1}^\infty$ converges uniformly on E to a function f if

$$\forall \epsilon > 0, \exists N \in \mathbb{N} \text{ such that } \forall x \in E, n \geq N \implies |f_n(x) - f(x)| \leq \epsilon.$$

Also, we say that the series $\sum f_n(x)$ converges uniformly on E if the sequence of partial sums $(\sum_{k=1}^n f_k(x))$ converges uniformly on E .

점별수렴의 경우 $N_x \in \mathbb{N}$ 이 $x \in E$ 에 의존하지만, 고른수렴의 경우 N 이 x 와 무관합니다!

[똑같은 ϵ -띠를 둘러서 $y = f(x)$ 의 근방 안에 $f_n(x)$ ($n \geq N$) 가 모두 들어가 있어야 한다]는 의미에서 uniform입니다. 한꺼번에 ϵ 으로 누를 수 있다는 것입니다.

Theorem 7.9 Suppose

$$f(x) = \lim_{n \rightarrow \infty} f_n(x) \quad (x \in E)$$

Then $f_n \rightarrow f$ converges uniformly on E if and only if

$$\lim_{n \rightarrow \infty} \sup_{x \in E} |f_n(x) - f(x)| = 0$$

which can also be written as

$$\forall \epsilon > 0, \exists N \in \mathbb{N} \text{ such that } n \geq N \implies \sup_{x \in E} |f_n(x) - f(x)| \leq \epsilon$$

Notation. $f_n \rightarrow f$ uniformly on $E \iff f_n \xrightarrow{u} f$ on E .⁴

Theorem 7.8 (Cauchy Criterion for Uniform Convergence) $f_n \xrightarrow{u} f$ on $E \iff$

²Subspace of metric space is also a metric space.

³갑자기 왜 uniform continuity 얘기를 하나, 헛갈리지 말고 기억하시라고!

⁴교수님: 책에서는 나중에 $\|f_n(x) - f(x)\|_\infty \rightarrow 0$ 으로 적었던 것 같은데...

$$\forall \epsilon > 0, \exists N \in \mathbb{N} \text{ such that } n, m \geq N \implies \sup_{x \in E} |f_n(x) - f_m(x)| \leq \epsilon. \text{ }^5$$

Proof.

(\implies) For given $\epsilon > 0$, fix $x \in E$. Since f_n converges uniformly on E , we can find $N \in \mathbb{N}$ such that for $n, m \geq N$,

$$|f_n(x) - f_m(x)| \leq |f_n(x) - f(x)| + |f(x) - f_m(x)| \leq \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$$

(\impliedby) Uniform Cauchy property implies that (f_n) is a Cauchy sequence in \mathbb{C} . By the completeness of \mathbb{C} , the limit function $f(x)$ exists. Now we show that this convergence is uniform. For given $\epsilon > 0$ choose $N \in \mathbb{N}$ such that for all $n, m \geq N$,

$$\sup_{x \in E} |f_n(x) - f_m(x)| \leq \epsilon$$

Then

$$\begin{aligned} |f_n(x) - f(x)| &= |f_n(x) - f_m(x) + f_m(x) - f(x)| \leq |f_n(x) - f_m(x)| + |f_m(x) - f(x)| \\ &\leq |f_m(x) - f(x)| + \epsilon \end{aligned}$$

Fix $n \geq N$ and let $m \rightarrow \infty$. Observe that $|f_m(x) - f(x)| \rightarrow 0$ due to pointwise convergence. Therefore for every $x \in E$,

$$n \geq N \implies |f_n(x) - f(x)| \leq \epsilon.$$

코시 수열이 중요한 이유는 completeness 뿐만 아니라, 극한값을 알지 못할 때 수열의 수렴성을 논할 수 있기 때문입니다. 특히 급수의 경우 그 극한값을 알 수 없기 때문에 급수의 수렴판정 등에서 유용하게 사용됩니다.

⁵Uniform Cauchy Property. 실수에서 알고있던 성질과 동일합니다.

September 6th, 2022

More examples.

Example 7.5 Consider $f_n(x) = \frac{\sin nx}{\sqrt{n}}$ for $x \in \mathbb{R}$.

$$f(x) = \lim_{n \rightarrow \infty} f_n(x) \equiv 0$$

but,

$$f'_n(x) = \sqrt{n} \cos nx \implies f'_n(0) = \sqrt{n}.$$

As $n \rightarrow \infty$, $f'_n(0)$ does not converge to $f'(0)$.

Example 7.6 Consider $f_n(x) = nx(1 - x^2)^n$ for $x \leq 0 \leq 1$. Note that

$$f_n(0) = 0, f_n(1) = 0.$$

When $0 < x < 1$, $f_n \rightarrow f \equiv 0$. (Theorem 3.20 (d)) Thus $\lim_{n \rightarrow \infty} f_n(x) = 0$ for $0 \leq x \leq 1$.

But

$$\int_0^1 nx(1 - x^2)^n dx = \left[\frac{-n}{2n+2} (1 - x^2)^{n+1} \right]_0^1 = \frac{n}{2n+2},$$

and thus

$$\lim_{n \rightarrow \infty} \int_0^1 f_n(x) dx = \frac{1}{2} \neq 0 = \int_0^1 f(x) dx.$$

Definition. $\sum_{n=1}^{\infty} f_n$ converges uniformly on $E \iff \left(\sum_{k=1}^n f_k \right)$ converges uniformly on E .

Theorem 7.10 (Weierstrass M -test) Suppose $f_n : E \rightarrow \mathbb{C}$ and that for every n , $\exists M_n \in \mathbb{R}$ such that

$$|f_n(x)| \leq M_n, \quad (x \in E)$$

and $\sum_{n=1}^{\infty} M_n < \infty$. Then the series $\sum_{n=1}^{\infty} f_n$ converges uniformly on E .

Proof. We want to show that the series is Cauchy.

For $m > n$, we have

$$\left| \sum_{k=n}^m f_k(x) \right| \leq \sum_{k=n}^m |f_k(x)| \leq \sum_{k=n}^m M_k.$$

Given $\epsilon > 0$, choose $m, n \in \mathbb{N}$ such that for $m, n \geq N$, $\sum_{k=n}^m M_k < \epsilon$. Then we get

$$\left| \sum_{k=n}^m f_k(x) \right| < \epsilon, \text{ for all } m, n \geq N.$$

By Theorem 7.8, $\sum f_n$ converges uniformly.

Theorem 7.11 Given metric space (Y, d) and $E \subseteq Y$, suppose that $f_n \xrightarrow{u} f$ on E and $x \in E'$.
If

$$\lim_{t \rightarrow x} f_n(t) = A_n \in \mathbb{C}, \quad (\text{limit exists})$$

then the sequence (A_n) converges, and

$$\lim_{n \rightarrow \infty} A_n = \lim_{t \rightarrow x} f(t).$$

In conclusion,

$$\lim_{n \rightarrow \infty} \lim_{t \rightarrow x} f_n(t) = \lim_{t \rightarrow x} \lim_{n \rightarrow \infty} f_n(t).$$

Proof. ⁶

$((A_n)$ converges in \mathbb{C}) Since \mathbb{C} is complete, we will show that (A_n) is a Cauchy sequence. Let $\epsilon > 0$. Since $f_n \xrightarrow{u} f$ on E ,

$$\exists N \in \mathbb{N} \text{ such that } n, m \geq N \implies |f_n(t) - f_m(t)| \leq \epsilon. \quad (\forall t \in E)$$

From $\lim_{t \rightarrow x} f_n(t) = A_n$, we can choose t arbitrarily close to x , such that for $n, m \geq N$,

$$|f_n(t) - A_n| < \epsilon \text{ and } |f_m(t) - A_m| < \epsilon.$$

Therefore for all $n, m \geq N$,

$$\begin{aligned} |A_n - A_m| &= |A_n - f_n(t) + f_n(t) - A_m + f_m(t) - f_m(t)| \\ &\leq |f_n(t) - A_n| + |f_m(t) - A_m| + |f_n(t) - f_m(t)| < 3\epsilon, \end{aligned}$$

and thus (A_n) is a Cauchy Sequence.

$(\lim_{n \rightarrow \infty} A_n = \lim_{t \rightarrow x} f(t))$ Let $A = \lim_{n \rightarrow \infty} A_n$. We want to show that for all $\epsilon > 0$,

$$\exists \delta > 0 \text{ such that } 0 < d(t, x) < \delta \implies |f(t) - A| < \epsilon.$$

Now,

$$|f(t) - A| \leq \sup_{s \in E} |f(s) - f_n(s)| + |f_n(t) - A_n| + |A_n - A|.$$

Given $\epsilon > 0$, choose $N \in \mathbb{N}$ such that for $n \geq N$,

$$\sup_{s \in E} |f(s) - f_n(s)| < \frac{\epsilon}{3} \text{ and } |A_n - A| < \frac{\epsilon}{3}.$$

Fix such N and choose δ such that for $0 < d(x, t) < \delta$ and $t \in E$,

$$|f_N(t) - A_N| \leq \frac{\epsilon}{3}.$$

⁶고른수렴이 어디에서 쓰였는지 확인하는 것이 중요하다.

Thus for $t \in E$ and $0 < d(x, t) < \delta$,

$$|f(t) - A| \leq \frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3} = \epsilon.$$

Theorem 7.12 Suppose $f: E \rightarrow \mathbb{C}$ is continuous on E and $f_n \xrightarrow{u} f$ on E . Then f is continuous on E .

Proof. Let $x \in E$. If $x \in E'$, f is continuous at x by Theorem 7.11. If x is an isolated point (not a limit point), f is continuous at x by definition of continuity.

고른수렴이 연속함수열의 올바른 수렴입니다.

앞으로는 E 를 전부 metric space라고 가정할게요.

이 정리는 언제 uniformly converge 하는지 알려줍니다.

Theorem 7.13 Given a compact metric space K , suppose that

(1) f_n and $f : K \rightarrow \mathbb{C}$ are continuous on K .

(2) $f_n \rightarrow f$ pointwise.

(3) $f_n(x) \geq f_{n+1}(x)$ for $x \in K$.⁷

Then $f_n \xrightarrow{u} f$ on K .

Proof. Let $g_n(x) = f_n(x) - f(x)$. Then $g_n(x)$ is continuous, decreasing and $g_n \rightarrow 0$ as $n \rightarrow \infty$ for all $x \in K$. Let $\epsilon > 0$ be given.

Claim. There exists $N \in \mathbb{N}$ such that $0 \leq g_n(x) < \epsilon$ for all $x \in K$.

Proof. Let $K_n = \{x \in K : g_n(x) \geq \epsilon\}$. Then $K_n = K \cap g_n^{-1}([\epsilon, \infty))$.⁸ Since g_n is decreasing, $K_{n+1} \subseteq K_n$, but because $g_n \rightarrow 0$, $\bigcap_{n=1}^{\infty} K_n = \emptyset$. By Theorem 2.36, there exists $N \in \mathbb{N}$ such that $K_N = \emptyset$, and then $K_n = \emptyset$ for $n \geq N$. Thus, $0 \leq g_n(x) < \epsilon$ for $\forall x \in K, \forall n \geq N$.

Remark. Compactness is necessary here. Consider $f_n(x) = \frac{1}{nx+1}$ on $x \in E = (0, 1)$. f_n does not converge to 0 uniformly.

Proof. Suppose $f_n \xrightarrow{u} 0$, and take $\epsilon = 1/2$. Then,

$$\exists N \in \mathbb{N} \text{ such that } x \in (0, 1) \implies \frac{1}{Nx+1} < \frac{1}{2}.$$

⁷ f_n only needs to be monotone. See Dini's Theorem.

⁸Closed subset of a compact set is also compact, and the inverse image of closed set is closed if the function is continuous

This gives a contradiction because the equation above gives $Nx > 1$, but we can choose x arbitrarily close to 0.

Definition. Let (X, d) be a metric space. Define

$$C(X, \mathbb{C}) = \{f : X \rightarrow \mathbb{C} \mid f \text{ is continuous and bounded}\}.$$

If there is no ambiguity, we write $C(X) = C(X, \mathbb{C})$.

Let $\|f\| = \sup_{x \in X} |f(x)|$. Then $\|\cdot\|$ is a norm on $C(X)$, and we call it **sup norm**.

$$(1) \quad \|f\| = 0 \iff f \equiv 0.$$

$$(2) \quad \|f\| < \infty, \|\alpha f\| = |\alpha| \|f\| \text{ for } \alpha \in \mathbb{C}.$$

$$(3) \quad \|f + g\| \leq \|f\| + \|g\|.$$

Define $d(f, g) = \|f - g\|$, then $(C(X), d)$ is a metric space.

Therefore, $f_n \xrightarrow{u} f \iff f_n \rightarrow f$ in $(C(X), d)$.

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Theorem 7.15 $(C(X), \|\cdot\|)$ is a complete metric space.

Proof.⁹ Suppose (f_n) is a Cauchy sequence in $C(X)$. By Theorem 7.8, $\exists f : X \rightarrow \mathbb{C}$ such that $f_n \xrightarrow{u} f$ in X . Also by Theorem 7.12, f is continuous on X .

Choose $N \in \mathbb{N}$ such that $\|f_N - f\| \leq 1$. Then

$$\|f\| \leq \|f_N - f\| + \|f_N\| \leq 1 + \|f_N\| < \infty,$$

and f is bounded. Therefore $f \in C(X)$, and $C(X)$ is complete.

다시 돌아와서 고른수렴이 리만적분가능성과 미분가능성을 보존하는지 확인합니다.

Theorem 7.16 Let $\alpha : [a, b] \rightarrow \mathbb{R}$ be a monotonically increasing function. Suppose that

$$(1) f_n \in \mathcal{R}(\alpha),$$

$$(2) f_n \xrightarrow{u} f \text{ on } [a, b].$$

Then $f \in \mathcal{R}(\alpha)$ and $\int_a^b f d\alpha = \lim_{n \rightarrow \infty} \int_a^b f_n d\alpha$.

Proof. WLOG, let $f_n : [a, b] \rightarrow \mathbb{R}$. We know that f_n, f are bounded.¹⁰

Let $\epsilon_n = \sup_{x \in [a, b]} |f_n(x) - f(x)| < \infty$, and because $f_n \xrightarrow{u} f$, $\epsilon_n \rightarrow 0$ as $n \rightarrow \infty$. Therefore

$$f_n - \epsilon_n \leq f \leq f_n + \epsilon_n$$

since upper/lower integrals preserve monotonicity,

$$\int_a^b (f_n - \epsilon_n) d\alpha = \int_a^b (f_n - \epsilon_n) d\alpha \leq \int_a^b f d\alpha \leq \overline{\int_a^b f d\alpha} \leq \overline{\int_a^b (f_n + \epsilon_n) d\alpha} = \int_a^b (f_n + \epsilon_n) d\alpha.$$

The equality at each end is given by $f_n \pm \epsilon_n \in \mathcal{R}(\alpha)$. Thus,

$$0 \leq \overline{\int_a^b f d\alpha} - \int_a^b f d\alpha \leq 2 \int_a^b \epsilon_n d\alpha = 2\epsilon_n(\alpha(b) - \alpha(a)),$$

and $f \in \mathcal{R}(\alpha)$. Moreover,

$$\left| \int_a^b f_n d\alpha - \int_a^b f d\alpha \right| \leq \epsilon_n(\alpha(b) - \alpha(a)) \rightarrow 0$$

as $n \rightarrow \infty$ gives the existence of the limit.

⁹코시 수열이 수렴하며 수렴값이 $C(X)$ 에 있는지 보이면 된다.

¹⁰Why?

Corollary. Suppose $f_n \in \mathcal{R}(\alpha)$ on $[a, b]$ and $\sum f_n(x)$ converges uniformly. Then

$$\int_a^b \sum_{n=1}^{\infty} f_n d\alpha = \sum_{n=1}^{\infty} \int_a^b f_n d\alpha.$$

Theorem 7.17 For sequence of functions f_n defined on $[a, b]$, suppose the following.

- (1) f_n is differentiable on $[a, b]$.
- (2) For some point $x_0 \in [a, b]$, $(f_n(x_0))_{n=1}^{\infty}$ converges.
- (3) f'_n converges uniformly on $[a, b]$.

Then the following holds.

$$(R1) \quad f_n \xrightarrow{u} f \text{ on } [a, b].$$

$$(R2) \quad f'(x) = \lim_{n \rightarrow \infty} f'_n(x).$$

Proof. Let $\epsilon > 0$ be given. We choose $N \in \mathbb{N}$ such that for $n, m \geq N$ and $t \in [a, b]$,

$$|f_n(x_0) - f_m(x_0)| < \frac{\epsilon}{2} \text{ and } |f'_n(t) - f'_m(t)| < \frac{\epsilon}{2(b-a)}.$$

Then for $n, m \geq N$, by using the Mean Value Theorem on $f_n - f_m$,

$$|f_n(x) - f_m(x) - f_n(t) + f_m(t)| \leq |x - t| \cdot \frac{\epsilon}{2(b-a)} \leq \frac{\epsilon}{2}. \quad (*)$$

Thus, set $t = x_0$ to get

$$|f_n(x) - f_m(x)| \leq |f_n(x) - f_m(x) - f_n(x_0) + f_m(x_0)| + |f_n(x_0) - f_m(x_0)| < \frac{\epsilon}{2} + \frac{\epsilon}{2} < \epsilon$$

and (R1) is proven. Let $f(x) = \lim_{n \rightarrow \infty} f_n(x)$.

For (R2), fix $x \in [a, b]$. Define

$$\phi_n(t) = \frac{f_n(t) - f_m(x)}{t - x}, \quad \phi(t) = \frac{f(t) - f(x)}{t - x},$$

for $t \in [a, b] \setminus \{x\}$. Then for each n ,

$$\lim_{t \rightarrow x} \phi_n(t) = f'_n(x).$$

We want to show that $\phi_n \xrightarrow{u} \phi$ (on $t \neq x$), so that

$$f'(x) = \lim_{t \rightarrow x} \phi(t) = \lim_{t \rightarrow x} \lim_{n \rightarrow \infty} \phi_n(t) = \lim_{n \rightarrow \infty} \lim_{t \rightarrow x} \phi_n(t) = \lim_{n \rightarrow \infty} f'_n(x).$$

By (*), we see that for $n, m \geq N$,

$$|\phi_n(t) - \phi_m(t)| \leq \frac{\epsilon}{2(b-a)},$$

which directly shows that ϕ_n converges uniformly on $t \neq x$.

Remark. f'_n 의 연속성을 가정하면 적분을 이용해서 훨씬 간편하게 증명할 수 있습니다.

Remark. (2)번 조건이 조금 부자연스럽게 느껴질 수 있으나, 최소한의 조건으로 최대의 결과를 얻고 싶었던 것입니다. 사실 (R1) $f_n \xrightarrow{u} f$ 임을 가정에 포함시켜 버린다면, (R2)를 얻을 수 있습니다.

Corollary. For sequence of functions f_n defined on $[a, b]$, suppose the following.

- (1) f_n is differentiable on $[a, b]$.
- (2) $f_n \xrightarrow{u} f$ on $[a, b]$.
- (3) f'_n converges uniformly on $[a, b]$.

Then $f'(x) = \lim_{n \rightarrow \infty} f'_n(x)$.

Theorem 7.18 There exists $f \in C(\mathbb{R}, \mathbb{R})$ such that f' does not exist for all $x \in \mathbb{R}$.¹¹

Proof. Define $\varphi(x) = |x|$ for $x \in [-1, 1]$, and $\varphi(x+2) = \varphi(x)$. Then for all $x, y \in \mathbb{R}$,

- (1) $0 \leq \varphi \leq 1$,
- (2) $|\varphi(x) - \varphi(y)| \leq |x - y|$.

Now define

$$f(x) = \sum_{n=0}^{\infty} \left(\frac{3}{4}\right)^n \varphi(4^n x).$$

By (1), $0 \leq f(x) \leq \sum (3/4)^n$ and $f(x)$ converges uniformly by M -Test, hence continuous on \mathbb{R} . Now we show that f is nowhere differentiable.

Fix $x \in \mathbb{R}$, let $m \in \mathbb{N}$. Choose $\delta_m = \pm \frac{1}{2} \cdot 4^{-m}$ so that there are no integers between $4^m x$ and $4^m(x + \delta_m)$. If $n > m$, then $4^n \delta_m = \pm \frac{1}{2} \cdot 4^{n-m}$ is even. Then by periodicity,

$$a_n = \frac{\varphi(4^n(x + \delta_m)) - \varphi(4^n x)}{\delta_m} = 0.$$

¹¹브라운 운동도 또 하나의 예.

If $0 \leq n \leq m$, by (2),

$$|a_n| = \left| \frac{\varphi(4^n(x + \delta_m)) - \varphi(4^n x)}{\delta_m} \right| \leq \frac{|4^n \delta_m|}{|\delta_m|} = 4^n.$$

If $n = m$, by (3),

$$|a_m| = \left| \frac{4^m(x + \delta_m) - 4^m x}{\delta_m} \right| = 4^m.$$

Therefore,

$$\begin{aligned} \left| \frac{f(x + \delta_m) - f(x)}{\delta_m} \right| &= \left| \sum_{n=0}^{\infty} \left(\frac{3}{4} \right)^n a_n \right| \geq \overbrace{0}^{n > m} + \overbrace{\left(\frac{3}{4} \right)^m |a_m|}^{n=m} - \left| \sum_{n=0}^{m-1} \left(\frac{3}{4} \right)^n a_n \right| \\ &\geq 3^m - \sum_{n=0}^{m-1} \left(\frac{3}{4} \right)^n |a_n| \\ &\geq 3^m - \sum_{n=0}^{m-1} 3^n = \frac{3^m + 1}{2}. \end{aligned}$$

As $m \rightarrow \infty$, $\delta_m \rightarrow 0$, but the difference diverges. Thus f is not differentiable anywhere.

September 13th, 2022

Equicontinuous 하기 전에 7.23을 먼저 할게요. 7.23을 하기 위한 motivation 입니다.

Recall. (Bolzano-Weierstrass) Suppose (a_n) is a sequence in \mathbb{C} . If (a_n) is bounded, then there exists a convergent subsequence of (a_n) .

Recall. A sequence (a_n) in a metric space (E, d) is bounded if

$$\exists x_0 \in E \text{ and } \exists r > 0 \text{ such that } a_n \in B_r(x_0) \text{ for all } n \in \mathbb{N}.$$

Definition. Suppose $f_n : E \rightarrow \mathbb{C}$. We say that (f_n) is **pointwise bounded** on E if the sequence $(f_n(x))_{n=1}^\infty$ is bounded for all $x \in E$. Or equivalently,

$$\sup_{n \in \mathbb{N}} |f_n(x)| < \infty \text{ for each } x \in E.$$

Theorem 7.23 Suppose E is at most countable.¹² Suppose $f_n : E \rightarrow \mathbb{C}$ and (f_n) is pointwise bounded. Then there exists a subsequence (f_{n_k}) of (f_n) such that $(f_{n_k}(x))$ converges for all $x \in E$.

$$\exists (n_k) \text{ such that } f(x) = \lim_{k \rightarrow \infty} f_{n_k}(x) \text{ for each } x \in E.$$

Proof. *Diagonalization!* Let $E = (x_i)_{i=1}^\infty$. (Countable) Since $(f_n(x_1))$ is bounded, there exists a convergent subsequence by Bolzano-Weierstrass Theorem. Let the subsequence be $(f_{1,k})_{k=1}^\infty$. Similarly, since $(f_{1,k}(x_2))$ is bounded, there exists a convergent subsequence $(f_{2,k})_{k=1}^\infty$ of $(f_{1,k})_{k=1}^\infty$. Since $(f_{n,k})$ is pointwise bounded, we can repeat this procedure to get the next subsequence $(f_{n+1,k})_{k=1}^\infty$.

Now we arrange the sequence,

$$\begin{array}{ccccccc} f_{1,1} & f_{1,2} & f_{1,3} & f_{1,4} & \cdots & & \\ f_{2,1} & f_{2,2} & f_{2,3} & f_{2,4} & \cdots & & \\ f_{3,1} & f_{3,2} & f_{3,3} & f_{3,4} & \cdots & & \\ f_{4,1} & f_{4,2} & f_{4,3} & f_{4,4} & \cdots & & \\ \vdots & \vdots & \vdots & \vdots & \ddots & & \end{array}$$

and consider the diagonal elements. Then $\lim_{n \rightarrow \infty} f_{n,n}(x)$ converges for all $x \in E$. This is because $(f_{n+1,k})$ is always a subsequence of $(f_{n,k})$, and $(f_{n,k})$ was chosen to converge on $\{x_1, x_2, \dots, x_n\}$.

Definition 7.19 Suppose $f_n : E \rightarrow \mathbb{C}$.

- (1) (f_n) is pointwise bounded on E if there exists a finite valued function $\varphi : E \rightarrow \mathbb{R}^+$ such that

¹²Countable 이거나 그거보다 작아서 finite 이거나. Countable이 아니면 안돼요.

$$|f_n(x)| \leq \varphi(x) < \infty \text{ for all } x \in E.$$

(2) (f_n) is **uniformly bounded** on E if there exists $M > 0$ such that

$$|f_n(x)| < M, \forall x \in E \text{ and } n \geq 1.$$

Or equivalently,

$$\sup_{n \in \mathbb{N}} \sup_{x \in E} |f_n(x)| < \infty$$

Remark.

(1) Uniform boundedness implies pointwise boundedness, but the converse is false.

(2) Every uniformly convergent sequence of bounded functions is uniformly bounded.

Question. Let E be a compact metric space.

(1) Suppose that $(f_n)_{n=1}^{\infty}$ is uniformly bounded or continuous. Is there a pointwise convergent subsequence (f_{n_k}) of (f_n) ? **No.**

(2) Suppose that (f_n) converges pointwise and is uniformly bounded. Is there a uniformly convergent subsequence (f_{n_k}) of (f_n) ? **No.**

아래 2개의 예시는 위 질문에 대한 대답이 ‘아니오’임을 알려줍니다.

Example 7.20 Let

$$f_n(x) = \sin nx, \quad (x \in [0, 2\pi]).$$

f_n is uniformly bounded ($|\sin nx| \leq 1$). Suppose there exists a subsequence f_{n_k} such that $(f_{n_k}(x))$ converges for all $x \in [0, 2\pi]$. Then as $k \rightarrow \infty$, $f_{n_k}(x) - f_{n_{k+1}}(x) \rightarrow 0$ for all $x \in [0, 2\pi]$.

However, as $k \rightarrow \infty$,

$$\int_0^{2\pi} (f_{n_k} - f_{n_{k+1}})^2 dx \rightarrow \int_0^{2\pi} 0^2 dx = 0$$

by Theorem 11.32.¹³ But simple calculation shows that

$$\int_0^{2\pi} (f_{n_k} - f_{n_{k+1}})^2 dx = 2\pi,$$

which leads to a contradiction. Thus such subsequence cannot exist.

Example 7.21 Let

$$f_n(x) = \frac{x^2}{x^2 + (1 - nx)^2}, \quad (x \in [0, 1]).$$

¹³Lebesgue's theorem concerning integration of boundedly convergent sequences.

f_n is uniformly bounded (by 1), and $f_n \rightarrow 0$ pointwise. Also, note that $f_n(1/n) = 1$.

Suppose there exists a subsequence (f_{n_k}) such that $f_{n_k} \xrightarrow{u} 0$. Then, $\exists k_0 \in \mathbb{N}$ such that

$$\sup_{x \in [0,1]} |f_{n_{k_0}}(x)| < \frac{1}{2}. \quad (*)$$

However,

$$1 = \left| f_{n_{k_0}} \left(\frac{1}{n_{k_0}} \right) \right| \leq \sup_{x \in [0,1]} |f_{n_{k_0}}(x)| < \frac{1}{2},$$

leading to a contradiction. Thus such subsequence cannot exist.

Definition 7.22 Let (X, d) be a metric space, and $E \subseteq X$. Let \mathcal{F} be a family of complex-valued functions on E . We say that \mathcal{F} is **equicontinuous** on E if

$$\forall \epsilon > 0, \exists \delta > 0 \text{ such that } d(x, y) < \delta \implies |f(x) - f(y)| < \epsilon \text{ for all } x, y \in E, f \in \mathcal{F}.$$

That is, all $f \in \mathcal{F}$ are uniformly continuous on E with the same (ϵ, δ) in the definition.

f 가 하나라면 그냥 uniform continuity의 정의입니다. 그런데 f 가 family of functions이고, 이러한 ϵ 을 모든 f 에 대해서 잡을 수 있다는 의미에서 ‘equi’ 입니다.

Remark. (Example 7.21) Let $\mathcal{F} = (f_n)$. Then \mathcal{F} is not equicontinuous on E .

Proof. Suppose \mathcal{F} is equicontinuous on E . For $\epsilon = 1$, there should exist $\delta > 0$ such that

$$\forall x, y \in [0, 1] \text{ and } |x - y| < \delta \implies |f_n(x) - f_n(y)| < 1.$$

In particular, $|f_n(0) - f_n(1/n)| < 1$ if $1/n < \delta$, but $|f_n(0) - f_n(1/n)| = 1$. Contradiction.

Theorem 7.24 Let K be a compact set. Suppose $f_n \in C(K)$. If f_n converges uniformly on K , $\mathcal{F} = (f_n)$ is equicontinuous on K .

Proof. Let $\epsilon > 0$ be given. Since (f_n) is uniformly Cauchy, $\exists N \in \mathbb{N}$ such that for all $x \in E$,

$$n \geq N \implies |f_n(x) - f_N(x)| < \frac{\epsilon}{3}.$$

Since continuous function defined on a compact set is uniformly continuous,¹⁴ f_n is uniformly continuous. Therefore $\exists \delta > 0$ such that

$$d(x, y) < \delta \implies |f_N(x) - f_N(y)| < \frac{\epsilon}{3} \text{ for } x, y \in K.$$

For $x, y \in K$, if $n \geq N$ and $d(x, y) < \delta$,

$$|f_n(x) - f_n(y)| \leq |f_n(x) - f_N(x)| + |f_N(x) - f_N(y)| + |f_N(y) - f_n(y)| \leq \frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3} = \epsilon.$$

¹⁴Heine-Cantor Theorem.

Therefore $(f_n)_{n=N}^{\infty}$ is equicontinuous. Additionally, $(f_n)_{n=1}^N$, which is a finite union of uniformly continuous functions, is equicontinuous. Thus (f_n) is equicontinuous because it is a union of two equicontinuous family of functions.¹⁵

¹⁵유한개는 equicontinuous 로 누르고, 꼬리는 uniform convergence로 누르고.

September 15th, 2022

증명을 들여다 보면, 7.24의 조건이 optimal 조건은 아니에요.

Theorem 7.25 (Arzela-Ascoli) Let K be a compact set. Suppose $f_n \in C(K)$. (Bounded and continuous) Suppose that $(f_n)_{n=1}^\infty$ is pointwise bounded and equicontinuous on K . Then

- (1) $(f_n)_{n=1}^\infty$ is uniformly bounded on K .
- (2) There exists a subsequence $(f_{n_k})_{k=1}^\infty$ which converge uniformly on K .

Proof. Since (f_n) is equicontinuous on K , choose $\epsilon = 1$. Then $\exists \delta > 0$ such that for all $n \in \mathbb{N}$,

$$\forall x, y \in K, d(x, y) < \delta \implies |f_n(x) - f_n(y)| < 1. \quad (*)$$

Since K is compact and $K \subseteq \bigcup_{x \in K} B_\delta(x)$,

$$\exists x_1, \dots, x_r \in K \text{ such that } K \subseteq \bigcup_{j=1}^r B_\delta(x_j).$$

By (*), for all $n \in \mathbb{N}$ and $j = 1, \dots, r$,

$$|f_n(x)| \leq |f_n(x_j)| + 1, \quad \forall x \in B_\delta(x_j).$$

Then we see that $\|f_n\| \leq \max_{1 \leq j \leq r} |f_n(x_j)| + 1$, for all $n \in \mathbb{N}$. Now since (f_n) is pointwise bounded,

$$\sup_{n \in \mathbb{N}} \|f_n\| \leq \sup_{n \in \mathbb{N}} \max_{1 \leq j \leq r} |f_n(x_j)| + 1 < \infty,$$

showing that (f_n) is uniformly bounded.

From Problem 2.25, a compact set has a countable dense subset. Let $E \subseteq K$ be such subset. (극한점이거나, E 의 원소이거나) By Theorem 7.23, there exists a subsequence $g_i = f_{n_i}$ such that (g_i) converges pointwise in E .

Let $\epsilon > 0$ be given. We know that (g_i) is equicontinuous, $\exists \delta > 0$ such that for all $i \in \mathbb{N}$

$$\forall x, y \in K, d(x, y) < \delta \implies |g_i(x) - g_i(y)| < \frac{\epsilon}{3}. \quad (**)$$

Because E is dense, $K \subseteq \bigcup_{x \in E} B_\delta(x)$. Compactness of K gives

$$\exists x_1, \dots, x_m \in E \text{ such that } K \subseteq \bigcup_{s=1}^m B_\delta(x_s).$$

Then for any $x \in K$, there exists $s \leq m$ such that $x \in B_\delta(x_s)$. By (**), for all $i \in \mathbb{N}$,

$$|g_i(x) - g_i(x_s)| < \frac{\epsilon}{3}.$$

Since g_i converges pointwise in E , $\exists N \in \mathbb{N}$ such that for $i, j \geq N$,

$$|g_i(x_s) - g_j(x_s)| < \frac{\epsilon}{3}. \quad (s = 1, \dots, m)$$

Therefore, for all $i, j \geq N$ and $x \in K$,

$$\begin{aligned} |g_i(x) - g_j(x)| &\leq |g_i(x) - g_i(x_s)| + |g_i(x_s) - g_j(x_s)| + |g_j(x_s) - g_j(x)| \\ &< \frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3} = \epsilon. \end{aligned}$$

언제 uniformly converge 하는 subsequence가 존재하는지에 대한 조건들을 배운 것입니다.

Weierstrass Theorem. 어떤 관점으로 보면 좋다면, 실제로 sin, cos 전개도 안하고 쪽 얘기를 하고 있어요. 거리 공간에서 정의된 연속함수들의 공간을 생각하는데, 구체적인 함수 얘기가 없어요. 그렇다고 모든 연속함수를 구체적으로 적을 수는 없죠. (구체적이라는 것의 정의도 애매하지만) 다 정리를 못한다면, 어느 정도 근사하는 방법으로 정리할 수 있는가?

모든 연속함수는 다항식으로 근사 가능하다! Compact 하면 uniformly 근사가 된다.

Theorem 7.26 (Weierstrass) Suppose $f \in C([a, b], \mathbb{C})$. ($a, b \in \mathbb{R}$) Then there exists a sequence of polynomials $P_n \in C([a, b], \mathbb{C})$ such that

$$\lim_{n \rightarrow \infty} P_n(x) = f(x)$$

uniformly on $[a, b]$. If f is real, P_n may be taken real.

여러 가지 증명 방법이 있는데, 책의 증명이 굉장히 교육적입니다. 몇 가지 중요한 테크닉, 배울 점이 많은 증명이에요.

Proof. WLOG, we prove the theorem on $[0, 1]$ and we extend to \mathbb{R} by letting $f \equiv 0$ on $\mathbb{R} \setminus [0, 1]$.

We first assume that $f(0) = f(1) = 0$.

Then f is uniformly continuous on \mathbb{R} . We will find polynomials Q_n and let¹⁶

$$P_n(x) = \int_{-1}^1 f(x+t)Q_n(t) dt.$$

¹⁶Idea. P_n 의 모양은 간단해요. 이런걸 convolution 이라고 부르는데... P_n 이 정말로 근사가 된다는걸 보이기 위해 $|P_n - f|$ 같은걸 해야하죠. Q_n 은 n 이 커짐에 따라 점점 몰아주고, $f(x+t) - f(x)$ 를 작게 만들고 싶습니다.

Let

$$Q_n(x) = c_n(1 - x^2)^n, \quad c_n = \left(\int_{-1}^1 (1 - x^2)^n dx \right)^{-1},$$

where c_n is chosen to satisfy $\int_{-1}^1 Q_n(x) dx = 1$. We need to control the size of c_n , so define

$$g(x) = (1 - x^2)^n - (1 - nx^2).$$

Then $g(0) = 0$, $g'(x) = 2nx(1 - (1 - x^2)^{n-1}) \geq 0$ for $x \in [0, 1]$. ($g(x) \geq 0$) Thus,

$$\int_{-1}^1 (1 - x^2)^n dx = 2 \int_0^1 (1 - x^2)^n dx \geq 2 \int_0^{1/\sqrt{n}} (1 - nx^2) dx = \frac{4}{3\sqrt{n}} > \frac{1}{\sqrt{n}},$$

therefore $c_n \leq \sqrt{n}$.

By change of variables $s = x + t$ and because $f \equiv 0$ on $\mathbb{R} \setminus [0, 1]$,

$$P_n(x) = \int_0^1 f(s)Q_n(s - x) ds = c_n \int_0^1 f(s)(1 - s^2 + 2sx - x^2)^n dx.$$

The integral above is clearly a polynomial in x . Thus (P_n) is a sequence of polynomials.

Given $\epsilon > 0$, choose $\delta \in (0, 1)$ such that

$$a, b \in [0, 1], |a - b| < \delta \implies |f(a) - f(b)| < \frac{\epsilon}{2}.$$

Now,

$$|P_n(x) - f(x)| \leq \int_{-1}^1 |f(x + t) - f(x)| Q_n(t) dt.$$

Split the last integral to $[-1, 1] = [-1, -\delta] \cup [-\delta, \delta] \cup [\delta, 1]$. Then we see that

$$\int_{-\delta}^{\delta} |f(x + t) - f(x)| Q_n(t) dt < \frac{\epsilon}{2} \int_{-\delta}^{\delta} Q_n(t) dt,$$

$$\int_{-1}^{-\delta} |f(x + t) - f(x)| Q_n(t) dt + \int_{\delta}^1 |f(x + t) - f(x)| Q_n(t) dt < 4c_n \|f\| (1 - \delta^2)^n,$$

since $Q_n(t) \leq c_n(1 - \delta^2)^n$.

Let $N \in \mathbb{N}$ such that for $n \geq N$,

$$4 \|f\| \sqrt{n}(1 - \delta^2)^n < \frac{\epsilon}{2}.$$

Then we finally have

$$|P_n(x) - f(x)| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$$

for $n \geq N$.

In general, let

$$g(x) = f(x) - f(0) - x(f(1) - f(0))$$

so that $g(1) = g(0) = 0$. By the previous case, there exists $P_n^* \xrightarrow{u} g$ on $[0, 1]$. Then

$$P_n(x) = P_n^*(x) + f(0) + x(f(1) - f(0)) \xrightarrow{u} f$$

on $[0, 1]$.

September 20, 2022

Weierstrass: 닫힌 구간에서 정의된 연속함수는 다항식으로 uniformly 근사할 수 있다!

Corollary. For $a > 0$, $\exists P_n \in C([-a, a], \mathbb{R})$ such that

$$P_n(0) = 0 \text{ and } P_n(x) \xrightarrow{u} |x| \text{ on } [-a, a].$$

Proof. By Weierstrass Theorem, there exists $P_n^*(x) \in C([-a, a], \mathbb{R})$ such that $P_n^*(x) \xrightarrow{u} |x|$ on $[-a, a]$. Let $P_n(x) = P_n^*(x) - P_n^*(0)$ so that $P_n(0) = 0$. Then $P_n(x)$ will have the desired property.

Definition 7.28 Given a metric space (E, d) , let \mathcal{A} be a collection of complex-valued functions on E .

(1) \mathcal{A} is called an **algebra**¹⁷ if

$$f + g, f \cdot g, cf \in \mathcal{A} \text{ whenever } f, g \in \mathcal{A}, c \in \mathbb{C}.$$

(2) Algebra \mathcal{A} is **uniformly closed** if

$$f_n \in \mathcal{A} \text{ and } f_n \xrightarrow{u} f \text{ then } f \in \mathcal{A}.$$

(3) For a given algebra \mathcal{A} ,

$$\mathcal{B} = \{f : \exists f_n \in \mathcal{A} \text{ such that } f_n \xrightarrow{u} f\}$$

is called the **uniform closure** of \mathcal{A} . We write $\mathcal{B} = \overline{\mathcal{A}}^{\|\cdot\|} = \overline{\mathcal{A}}^u$.

Example. Examples of algebras. ($[a, b]$ can be changed to compact sets.)

(1) $\mathcal{A} = \{f : f \in C([a, b])\}$.

(2) $\mathcal{A} = \{f : f \text{ is bounded on } [a, b]\}$.

(3) $\mathcal{A} = \{f : f \text{ is a polynomial on } [a, b]\}$.

Also note that $\overline{\mathcal{A}}^u = C([a, b])$ by Theorem 7.12 + Weierstrass Theorem.

Question. We are interested in $C(E, \mathbb{R})$ and $C(E, \mathbb{C})$ when E is a compact metric space. *We want to find an algebra whose uniform closure is $C(E, \mathbb{R})$ or $C(E, \mathbb{C})$.*

Theorem 7.29 Let \mathcal{B} be the uniform closure of an algebra \mathcal{A} of bounded functions. Then \mathcal{B} is a uniformly closed algebra.

¹⁷Real-valued functions의 경우 real algebra라고 부르고 $c \in \mathbb{R}$ 이다.

Proof. \mathcal{B} is uniformly closed by definition. Suppose that $f, g \in \mathcal{B}$ and $c \in \mathbb{C}$. By definition,

$$\exists f_n, g_n \in \mathcal{A} \text{ such that } f_n \xrightarrow{u} f, g_n \xrightarrow{u} g \text{ on } E.$$

Then $f_n + g_n \xrightarrow{u} f + g$, $f_n g_n \xrightarrow{u} f g$, $c f_n \xrightarrow{u} c f$ on E .¹⁸ Thus $f + g$, $f g$, $c f \in \mathcal{B}$, which makes \mathcal{B} a uniformly closed algebra.

Definition 7.30 Let \mathcal{A} be a family of functions on a set E .

(1) \mathcal{A} is said to **separate points** on E if

$$\text{for every distinct } x_1, x_2 \in E, \exists f \in \mathcal{A} \text{ such that } f(x_1) \neq f(x_2).$$

(2) \mathcal{A} **vanishes at no point** of E if

$$\forall x \in E, \exists f \in \mathcal{A} \text{ such that } f(x) \neq 0.¹⁹$$

Example.

(1) Set of polynomials on \mathbb{R} separates points on E and vanishes at no point of E .

(2) Even polynomials on $[-1, 1]$ does not separate points on E . ($f(x) = f(-x)$)

Theorem 7.31 Suppose that

(1) \mathcal{A} is an algebra of functions on a set E ,

(2) \mathcal{A} separates points on E ,

(3) \mathcal{A} vanishes at no point of E .

Then for any distinct points $x_1, x_2 \in E$ and for all $c_1, c_2 \in \mathbb{C}$,

$$\text{there exists } f \in \mathcal{A} \text{ such that } f(x_1) = c_1 \text{ and } f(x_2) = c_2.$$

Proof. We want to find $f(x) = c_1 f_1(x) + c_2 f_2(x)$ where

$$f_1(x_1) = 1, f_1(x_2) = 0, f_2(x_1) = 0, f_2(x_2) = 1.$$

From the given assumptions, we can find $g, h, k \in \mathcal{A}$ such that

(1) $g(x_1) \neq g(x_2)$ (separates points),

(2) $h(x_1) \neq 0, k(x_2) \neq 0$ (vanishes at no point).

¹⁸ $f_n g_n \xrightarrow{u} f g$ works because the functions are bounded.

¹⁹ 모든 함수가 0인 점은 없다!

Let

$$u(x) = g(x)k(x) - g(x_1)k(x), \quad v(x) = g(x)h(x) - g(x_2)h(x).$$

Then $u(x_1) = v(x_2) = 0$, $u(x_2) \neq 0$, $v(x_1) \neq 0$. Therefore setting

$$f_1(x) = \frac{v(x)}{v(x_1)}, \quad f_2(x) = \frac{u(x)}{u(x_2)} \implies f(x) = \frac{c_1 v(x)}{v(x_1)} + \frac{c_2 u(x)}{u(x_2)} \in \mathcal{A}$$

will give the desired result.

Theorem 7.32 (Stone-Weierstrass) Let \mathcal{A} be a real algebra of real continuous functions on a compact set K . (i.e. $\mathcal{A} \subseteq C(K, \mathbb{R})$) If

- (1) \mathcal{A} separates points on K ,
- (2) \mathcal{A} vanishes at no point of K ,

the uniform closure of \mathcal{A} consists of all real continuous functions on K . (i.e. $\overline{\mathcal{A}}^u = C(K, \mathbb{R})$)

Proof. Let $\mathcal{B} = \overline{\mathcal{A}}^u$. We know that $\mathcal{B} \subseteq C(K, \mathbb{R})$. So we only need to show $\mathcal{B} \supseteq C(K, \mathbb{R})$.

(Step 1) $f \in \mathcal{B} \implies |f| \in \mathcal{B}$.

Let $a = \|f\| = \sup_{x \in K} |f(x)|$. Given $\epsilon > 0$, there exists a polynomial approximating $|x|$.

$$\exists c_1, \dots, c_n \in \mathbb{R} \text{ such that } \sup_{y \in [-a, a]} \left| \sum_{i=1}^n c_i y^i - |y| \right| < \epsilon.$$

Define $g = \sum_{i=1}^n c_i f^i \in \mathcal{B}$. Then (plugging $f(x)$ into y gives)

$$|g(x) - |f(x)|| = \left| \sum_{i=1}^n c_i (f(x))^i - |f(x)| \right| < \epsilon, \quad (x \in K).$$

Since \mathcal{B} is uniformly closed, $|f| \in \mathcal{B}$.

(Step 2) $f_1, \dots, f_n \in \mathcal{B} \implies \max\{f_1, \dots, f_n\}, \min\{f_1, \dots, f_n\} \in \mathcal{B}$.

For $f, g \in \mathcal{B}$, $f + g, f - g \in \mathcal{B}$. Also by Step 1, $|f + g|, |f - g| \in \mathcal{B}$. Thus

$$\max\{f, g\} = \frac{f + g}{2} + \frac{|f - g|}{2}, \quad \min\{f, g\} = \frac{f + g}{2} - \frac{|f - g|}{2} \in \mathcal{B}.$$

By induction, $\max\{f_1, \dots, f_n\}, \min\{f_1, \dots, f_n\} \in \mathcal{B}$.

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Now we fix $\epsilon > 0$ and $f \in C(K, \mathbb{R})$.

(Step 3) For each $x \in K$, there exists a function $g_x \in \mathcal{B}$ such that

$$g_x(x) = f(x) \text{ and } g_x(y) > f(y) - \epsilon \text{ for all } y \in K.$$

Since $\mathcal{A} \subseteq \mathcal{B}$, we can use Theorem 7.31. For every $y \in K$, $\exists h_y \in \mathcal{B}$ such that

$$h_y(x) = f(x) \text{ and } h_y(y) = f(y).$$

By (uniform) continuity of f and h_y , there exists $\delta_y > 0$ such that

$$d(y, t) < \delta_y \implies |h_y(t) - h_y(y)| + |f(t) - f(y)| < \epsilon.$$

Therefore,

$$|h_y(t) - f(t)| \leq |h_y(t) - f(y)| + |f(y) - f(t)| < \epsilon$$

for all $d(y, t) < \delta_y$. Now for all $t \in J_y = \{t \in K : d(y, t) < \delta_y\}$,

$$h_y(t) > f(t) - \epsilon. \tag{*}$$

Since K is compact, there exists a finite subcover.

$$\exists y_1, \dots, y_n \in K \text{ such that } K \subseteq \bigcup_{j=1}^n J_{y_j}.$$

We can rewrite (*) as

$$h_{y_j}(t) > f(t) - \epsilon, \quad (t \in J_{y_j}).$$

Now take maximum of these,

$$g_x(t) = \max\{h_{y_1}(t), \dots, h_{y_n}(t)\} > f(t) - \epsilon$$

for all $t \in K$. By Step 2, $g_x(t) \in \mathcal{B}$.

(Step 4) For all $f \in C(K, \mathbb{R})$, given $\epsilon > 0$, there exists $g \in \mathcal{B}$ such that $\|f - g\| < \epsilon$. (i.e. $g_n \xrightarrow{u} f$ on K) Since \mathcal{B} is uniformly closed, $f \in \mathcal{B}$.²⁰

For each $x \in K$, let $g_x \in \mathcal{B}$ be the function defined in Step 3. By continuity of g_x and f ,

$$\exists \delta_x > 0 \text{ such that } t \in V_x \implies |g_x(t) - g_x(x)| + |f(t) - f(x)| < \epsilon$$

²⁰임의의 $f \in C(K, \mathbb{R})$ 로 수렴하는 $g_n \in \mathcal{B}$ 를 잡을 수 있다는 뜻이므로, uniform closure의 정의에 의해 $f \in \mathcal{B}$ 이다.

where $V_x = \{t \in K : d(x, t) < \delta_x\}$. Therefore,

$$|g_x(t) - f(t)| \leq |g_x(t) - g_x(x)| + |g_x(x) - f(t)| < \epsilon, \quad (t \in V_x)$$

Since K is compact, there exists a finite subcover.

$$\exists x_1, \dots, x_m \in K \text{ such that } K \subseteq \bigcup_{j=1}^m V_{x_j}.$$

Now for $t \in V_{x_j}$, (as we did in Step 3)

$$g_{x_j}(t) < f(t) + \epsilon,$$

so $g(t) = \min\{g_{x_1}(t), \dots, g_{x_m}(t)\} < f(t) + \epsilon$. By Step 2, $g \in \mathcal{B}$, and by Step 3,

$$g(t) > f(t) - \epsilon.$$

Thus we have found a function $g \in \mathcal{B}$ such that $\|g - f\| < \epsilon$.

Dense 하면서 nice(?)한 함수공간을 찾을 수 있을까? 여러분이 자세히 봐야 알 수 있겠지만 real algebra인 것을 가정한 거죠? 이 chapter의 마지막 부분은, real이 아니고 complex라면 같은 내용이 성립하는가 입니다. 단, 한 조건이 더 필요합니다. 그 전에 정의 하나 하고 갑니다.

Definition. We call a complex algebra \mathcal{A} **self-adjoint** if $f \in \mathcal{A} \implies \bar{f} \in \mathcal{A}$.

Theorem 7.33 Let \mathcal{A} be a self-adjoint algebra of complex continuous functions on a compact set K . (i.e. $\mathcal{A} \subseteq C(K, \mathbb{C})$) If

- (1) \mathcal{A} separates points on K ,
- (2) \mathcal{A} vanishes at no point of K ,

the uniform closure of \mathcal{A} consists of all complex continuous functions on K . (i.e. $\overline{\mathcal{A}}^u = C(K, \mathbb{C})$)

Proof. Let $\mathcal{A}_{\mathbb{R}} = \{f \in \mathcal{A} : f(K) \subseteq \mathbb{R}\}$. Then it is easy to see that $\mathcal{A}_{\mathbb{R}}$ is a real algebra, and subset of $C(K, \mathbb{R})$.

Claim. $\mathcal{A}_{\mathbb{R}}$ separates points on K .

Proof. Let $x_1 \neq x_2$. There exists $f \in \mathcal{A}$ such that $f(x_1) = 1, f(x_2) = 0$. Write $f = u + iv$ where $u, v \in C(K, \mathbb{R})$. Since $\bar{f} \in \mathcal{A}$, we have

$$u = \frac{f + \bar{f}}{2} \in \mathcal{A}_{\mathbb{R}} \subseteq \mathcal{A}.$$

Moreover, $u(x_1) = f(x_1) = 1, u(x_2) = f(x_2) = 0$.

Claim. $\mathcal{A}_{\mathbb{R}}$ vanishes at no point of K .

Proof. Fix $x \in K$. Choose non-zero $g \in \mathcal{A}$. Choose $\lambda \in \mathbb{C}$ such that $\lambda g(x) > 0$, we define $f = \lambda g$ which can be written $f = u + iv$ where $u, v \in C(K, \mathbb{R})$. Similarly, $u \in \mathcal{A}_{\mathbb{R}}$ and $u(x) = \lambda g(x) > 0$.

From the 2 claims above, we know that $\overline{\mathcal{A}_{\mathbb{R}}}^u = C(K, \mathbb{R}) \subseteq \overline{\mathcal{A}}^u$, by Theorem 7.32. Suppose $f \in C(K, \mathbb{C})$, and write $f = u + iv$. Fix $\epsilon > 0$. There exists $\tilde{u}, \tilde{v} \in \mathcal{A}_{\mathbb{R}}$ such that

$$\|u - \tilde{u}\| + \|v - \tilde{v}\| < \epsilon.$$

Define $\tilde{f} = \tilde{u} + i\tilde{v} \in \mathcal{A}$. Then $\|f - \tilde{f}\| < \epsilon$, proving that $f \in \overline{\mathcal{A}}^u$.²¹

²¹Denseness를 보인 것입니다.

Chapter 8

Some Special Functions

Special Functions 라는 이론이 따로 있어요. 8장에서는 여러분들이 많이 아는 부분이 있어서 골라가면서 하고, 그래도 봐야할 것들은 조교님께 얘기해서 하라고 할게요.

첫 번째로 다룰 부분은 power series 인데 전에 얘기했던 내용입니다.

Recall. (Root Test) Given $\sum a_n$, let

$$\alpha = \limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|}.$$

(1) If $\alpha < 1$, $\sum a_n$ converges absolutely.

(2) If $\alpha > 1$, $\sum a_n$ diverges.

Definition. A **power series** in \mathbb{R} about the point a is a series in the form

$$\sum_{n=0}^{\infty} c_n(x-a)^n, \quad (x \in \mathbb{R}). \quad (\star)$$

c_n 's are called the **coefficients** of the series.

Definition. (Radius of Convergence) $R = (0, \infty]$ is called the **radius of convergence** if the series (\star) converges absolutely for $|x-a| < R$, and diverges for $|x-a| > R$. Here,

$$\frac{1}{R} = \limsup_{n \rightarrow \infty} \sqrt[n]{|c_n|}.$$
¹

Theorem 8.1 Suppose the series

$$f(x) = \sum_{n=0}^{\infty} c_n(x-a)^n$$

¹Theorem 3.39.

converges for $|x - a| < R$.

(1) f converges uniformly on $|x - a| \leq R - \epsilon$ for all $\epsilon \in (0, R)$.

(2) f is continuous and differentiable on $|x - a| < R$. Moreover,

$$f'(x) = \frac{d}{dx} \left(\sum_{n=0}^{\infty} c_n (x - a)^n \right) = \sum_{n=1}^{\infty} n c_n (x - a)^{n-1}$$

on $|x - a| < R$.

Proof.

(1) WLOG, let $a = 0$, and fix $\epsilon \in (0, R)$. Observe that

$$|c_n x^n| \leq |c_n| (R - \epsilon)^n$$

for $|x| \leq R - \epsilon$. By the root test, $\sum |c_n| (R - \epsilon)^n < \infty$. Now we know that $\sum c_n x^n$ converges uniformly on $|x| \leq R - \epsilon$ by Weierstrass M -test.

(2) Using $n^{1/n} \rightarrow 1$, we see that

$$\limsup_{n \rightarrow \infty} \sqrt[n]{n |c_n|} = \limsup_{n \rightarrow \infty} \sqrt[n]{|c_n|}.$$

Thus the two series have the same radius of convergence. So $\sum_{n=1}^{\infty} n c_n x^{n-1}$ converges on $|x| < R$, and converges uniformly on $|x| \leq R - \epsilon$ by (1).

Now by Theorem 7.17,² f is differentiable, and therefore continuous. Also,

$$f'(x) = \lim_{n \rightarrow \infty} \frac{d}{dx} \left(\sum_{k=1}^n c_k x^k \right) = \sum_{n=1}^{\infty} n c_n x^{n-1},$$

for any $|x| < R$. (We can always choose ϵ such that $|x| \leq R - \epsilon$.)

Corollary. Let $f : \mathbb{R} \rightarrow \mathbb{R}$. Under the assumptions of Theorem 8.1, f has derivatives of all orders in $(-R, R)$, and

$$f^{(k)}(x) = \sum_{n=k}^{\infty} n(n-1) \cdots (n-k+1) c_n (x-a)^{n-k}.$$

In particular,

$$f^{(k)}(a) = k! \cdot c_k.$$

² f_n 이 미분 가능하고, f_n, f'_n 이 모두 고르게 수렴하면 f 가 미분 가능하며 $f' = \lim f'_n$.

함수공간의 Story

우리가 해석개론1에서 실수를 공부하기 위해서 어떻게 했었는지 떠올려 보면, 절대 실수 하나 하나를 개별적으로 보지 않았습니다. 실수의 모임을 두고, 실수열을 공부하고, 위상적인 구조를 주는 등의 작업을 하고 나서야 실수를 제대로 이해할 수 있었습니다.

함수도 마찬가지입니다. 우리는 함수를 이해하기 위해서 함수 하나를 개별적으로 보는 것이 아니라, 함수가 속해있는 공간을 공부하는 것입니다. 실수를 공부할 때와 마찬가지로, 함수열을 공부하고, 위상적인 구조를 공부하며 함수공간을 이해하게 됩니다. 그런데 \mathbb{R}/\mathbb{R}^n 과 함수공간의 가장 큰 차이점은 좌표공간은 유한차원이지만, **함수공간은 무한차원**이라는 점입니다.

함수공간을 벡터공간으로 만들기는 했으나, 선형대수학의 대부분 정리들은 벡터공간의 차원이 유한이라는 가정이 필요하기 때문에, 공짜로 얻어지는 정리는 없습니다. 이로 인해 **norm을 도입**하게 됩니다.

Norm을 도입하게 되면 공간에 거리 개념이 생기므로, metric space를 논할 수 있게 되고, 자연스럽게 수렴성을 논할 수 있게 됩니다. 이와 동시에 Cauchy 수열의 개념도 생겨납니다. 그리고 open ball을 정의할 수 있고, open/closed set이 정의되고, compact set까지 정의하게 됩니다. 함수공간에서는 norm이 없으면 아무것도 할 수 없습니다. **함수공간에는 norm이 항상 존재합니다.**

그리고 마지막으로 이 norm과 수렴 개념을 바탕으로 Cauchy 수열이 수렴하는지 살펴봅니다. 함수공간을 너무 작게 잡으면, Cauchy 수열이 수렴하지 않을 수 있습니다. 그러면 더 함수를 넣어야 합니다. 함수를 넣다보면 또 새로운 Cauchy 수열이 생깁니다. 이 과정을 반복하여 다 넣게 되면 드디어 Cauchy 수열이 수렴하게 되고, 비로소 **completeness(완비)**를 만족하게 됩니다.³

해석개론2의 첫 장에서는 **연속함수열의 수렴**에 대해 공부했습니다. 연속함수의 공간 $C(X)$ 에서 점별수렴과 고른수렴이 있었는데, 극한함수 또한 연속이어야 하기 때문에 우리는 이 함수공간에서 **고른수렴**을 올바른 수렴의 정의로 선택했습니다. 그래야 $C(X)$ 의 Cauchy 수열이 수렴하여 $C(X)$ 가 completeness를 만족하게 되기 때문입니다.

또 고른수렴에 대해서 공부하면서 얻은 부산물로, 고른수렴이 언제 미분가능성과 적분가능성을 보존하는지 공부했습니다. 극한함수의 미분가능성에 대해서는 굉장히 까다로운 조건이 필요했지만, 적분가능성의 경우 잘 보존되는 것을 확인했습니다. 이를 기점으로 해석학은 적분에 주안점을 두고 가게 됩니다. 우리가 함수를 미분하면 함수가 나빠지는 반면, 적분을 통해 얻은 함수는 상대적으로 다루기 쉽습니다. 또한 현실 세계에서 미분가능한 함수를 만나기 쉽지 않기도 합니다. **결국 해석학은 적분을 발전시키는 방향으로 나아가게 됩니다.**

수렴을 공부한 이후, 본격적으로 함수공간 $C(X)$ 를 공부했습니다. 이제 우리의 관심사는 $C(X)$

³Complete normed space를 Banach space라고 부릅니다.

의 compact set 입니다. 따라서 수렴하는 부분수열에 대해 공부하게 됩니다.⁴ 이는 마치 R^n 에서 Bolzano-Weierstrass 정리를 공부했던 것과 동일합니다. 그래서 $C(X)$ 의 수렴하는 부분수열을 찾기 위해 점별유계, 고른유계, 동등연속의 개념을 공부했으며 Arzela-Ascoli 정리를 공부했습니다. 그리고 실제로 주어진 연속함수로 수렴하는 연속함수열(특히 다항함수)이 존재한다는 사실을 Weierstrass 정리를 통해 공부했습니다. 이는 곧 \mathbb{Q} 가 \mathbb{R} 에서 조밀(dense)했던 것처럼 다항함수가 $C(X)$ 에서 조밀함을 보여줍니다.

수렴하는 부분수열이 중요한 또 다른 이유는 **precompact** 개념 때문이기도 합니다. 집합 X 의 수열이 수렴하는 부분수열을 가질 때, X 를 precompact set이라고 합니다. Precompact 개념을 이용하면 (f_n) 이 f 로 수렴하는지 확인하려 할 때, 이를 2단계로 나눠 증명할 수 있게 됩니다. 먼저 $\{f_n : n \in \mathbb{N}\}$ 이 precompact임을 보이고, (f_n) 의 부분수열이 g 로 수렴하면 $f = g$ 임을 보이면 됩니다.

이후로는 수열공간 $\ell^p(\mathbb{N})$, 특이적분가능함수공간 $\mathcal{R}^p(I)$ 에 대해 공부하게 되는데, 여기서도 같은 story가 반복됩니다. 함수공간을 벡터공간으로 만들어 norm을 정의하고, Cauchy 수열이 수렴하는지 확인하여 completeness를 확인합니다. 그리고 compact set에 대해 조사하게 됩니다. 수열공간 $\ell^p(\mathbb{N})$ 의 경우 유계이고 닫힌 집합만으로 compact set이 되기에는 부족함을 확인하게 되고,⁵ 특이적분가능함수공간 $\mathcal{R}^p(I)$ 는 complete 하지 않다는 것도 확인하게 됩니다. 이는 적분가능함수공간을 너무 작게 잡았다는 의미로, 후에 르벡 적분 등장 배경이 되며 르벡적분가능함수공간 $L^p(E)$ 는 completeness를 만족하게 됩니다.

⁴당연히 $C(X)$ 의 수렴은 고른수렴입니다.

⁵실제로, 무한차원의 normed space는 Heine-Borel property (compact \iff bounded & closed)를 가질 수 없음이 알려져 있습니다.

September 1st, 2022 (Practice)

해석개론 1 복습

1. Real Number System

Let $A \subseteq \mathbb{R}$.

- $b \in \mathbb{R}$ is an upper bound of A : $\forall a \in A \implies a \leq b$.
- $b \in \mathbb{R}$ is a lower bound of A : $\forall a \in A \implies a \geq b$.
- Least upper bound is denoted as $\sup A$.
- Greatest lower bound is denoted as $\inf A$.
- Least upper bound property: If $A \neq \emptyset$, $\exists \sup A$.
- Extended Real Numbers: $\overline{\mathbb{R}} = \mathbb{R} \cup \{\infty, -\infty\}$
- Now, if $\emptyset = A \subseteq \overline{\mathbb{R}}$, $\sup A = -\infty$.

2. Metric Spaces

Metric space: (X, d_X) where $d_X : X \times X \rightarrow \mathbb{R}$. For all $x, y, z \in X$ the following must hold.

- (1) $d_X(x, y) = 0 \iff x = y$.
- (2) $d_X(x, y) = d_X(y, x)$ (Symmetric)
- (3) $d_X(x, y) + d_X(y, z) \geq d_X(x, z)$

Notation. (Neighborhood) Ball of radius r , centered at p is denoted as

$$B_r(p) = \{x \in X \mid d_X(x, p) < r\}$$

- $U \subseteq X$ is open $\iff \forall p \in U, \exists r > 0$ such that $B_r(p) \subseteq U$.
- $C \subseteq X$ is closed $\iff C$ contains every limit point of C . Or alternatively, C^C is open.
- Union of open sets is open, finite intersection of open sets is open.
- $p \in B \subseteq X$ is a limit point of $B \iff \forall r \geq 0, (B_r(p) \setminus \{p\}) \cap B \neq \emptyset$.⁶
- A' is the set of limit points of A .

⁶임의의 근방에서 자기자신을 제외하고 B 의 점이 존재한다.

- $\overline{A} = A \cup A'$, which is the smallest closed set containing A .
- $A \subseteq X$ is dense in $X \iff \overline{A} = X$.
- $A \subseteq X$ is bounded $\iff \exists r > 0$ such that $A \subseteq B_r(p)$ for some $p \in X$.
- Sets A and B are separated $\iff \overline{A} \cap B = \emptyset = A \cap \overline{B}$.
- Set C is disconnected $\iff \exists$ non-empty separated sets A, B such that $C \subseteq A \cup B$.

Suppose $\{U_\alpha\}$ is a collection of open sets in X .

- $\{U_\alpha\}$ is an open cover of $A \iff A \subseteq \bigcup_{\alpha} U_\alpha$.
- $K \subseteq X$ is compact \iff for every open cover of K , there exists a finite subcover of K .

$$\exists \alpha_1, \alpha_2, \dots, \alpha_n \text{ such that } K \subseteq \bigcup_{k=1}^n U_{\alpha_k}$$

- (Heine-Borel) In \mathbb{R}^n , compact \iff bounded and closed.
- If K is compact and $A \subseteq K$ is closed, then A is also compact.
- If $\{K_\alpha\}$ is a collection of compact sets and $\bigcap_{\alpha} K_\alpha = \emptyset$, then

$$\exists \alpha_1, \alpha_2, \dots, \alpha_n \text{ such that } \bigcap_{k=1}^n K_{\alpha_k} = \emptyset.^7$$

3. Sequences

A sequence $a : \mathbb{N} \rightarrow A$, is a function. We write $a(i) = a_i$, and we usually consider sequences in metric spaces.

- $\{a_n\}$ converges to $\alpha \iff \forall \epsilon > 0, \exists N \in \mathbb{N}$ such that $n \geq N \implies d_X(a_n, \alpha) < \epsilon$.
- (Cauchy Sequence) $\{a_n\}$ is Cauchy
 $\iff \forall \epsilon > 0, \exists N \in \mathbb{N}$ such that $n, m \geq N \implies d_X(a_n, a_m) < \epsilon$.
- (X, d) is complete \iff every Cauchy sequence converges.⁸
- $\limsup_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} \sup\{a_k : k \geq n\}$.
- $\liminf_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} \inf\{a_k : k \geq n\}$.

⁷정의로 쉽게 보일 수 있다?

⁸수렴하면 코시 수열이지만, 모든 코시 수열이 수렴하지는 않는다. Consider any sequence of rational numbers converging to an irrational real number.

- $\lim a_n = \alpha \iff \limsup a_n = \liminf a_n = \alpha$ ($\alpha \in \mathbb{R}$).
- For power series $\sum a_n x^n$, the radius of convergence $R \in \overline{\mathbb{R}}$ is calculated as

$$\frac{1}{R} = \limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|}.$$

- Absolute convergence implies convergence.

4. Limit of Functions

Given metric spaces X, Y , define a function $f : E \subseteq X \rightarrow Y$.

- If $p \in E$ ⁹ then we can define $\lim_{x \rightarrow p} f(x) = \alpha$ as

$$\forall \epsilon > 0, \exists \delta > 0 \text{ such that } 0 < d_X(x, p) < \delta \implies d_Y(f(x), \alpha) < \epsilon.$$

Or equivalently, for any sequence $\{a_n\}$ in X with $a_n \neq p$,

$$\text{if } \lim_{n \rightarrow \infty} a_n = p \text{ then } \lim_{n \rightarrow \infty} f(a_n) = \alpha.$$

- f is continuous at $p \in E$ ¹⁰ \iff

$$\forall \epsilon > 0, \exists \delta > 0 \text{ such that } x \in E, d_X(x, p) < \delta \implies d_Y(f(x), f(p)) < \epsilon.$$

Or equivalently, for any sequence $\{a_n\}$ in X ,¹¹

$$\text{if } \lim_{n \rightarrow \infty} a_n = p \text{ then } \lim_{n \rightarrow \infty} f(a_n) = f(p).$$

- f is continuous \iff for any open set $V \subseteq Y$, $f^{-1}(V)$ is open in X .
- Suppose that f is continuous.
 - If $K \subseteq E$ is compact, $f(K)$ is also compact.
 - If $C \subseteq E$ is connected, $f(C)$ is also connected.
- (Extreme Value Theorem) Suppose $K \subseteq E$ is compact and $f : K \rightarrow \mathbb{R}$ is continuous. Because $f(K)$ is a compact set in \mathbb{R} , it is a closed interval. Hence f has a maximum/minimum.
- (Uniform Continuity) f is uniformly continuous on $E \iff$

$$\forall \epsilon > 0, \exists \delta > 0 \text{ such that } \forall x, \forall y \in E, d_X(x, y) < \delta \implies d_Y(f(x), f(y)) < \epsilon.$$

⁹함수의 극한은 극한점에서 논한다! 다가갈 점들이 있어야 하지 않겠는가?

¹⁰Limit point가 아니어도 정의할 수 있으며, 고립점에서는 연속이다.

¹¹여기서는 $a_n \neq p$ 조건이 빠진다.

- If $f : E \subseteq X \rightarrow Y$ is continuous and E is compact, f is uniformly continuous.

5. Differentiation

Function $f : [a, b] \rightarrow \mathbb{R}$ is differentiable at $x \in [a, b] \iff$

$$\text{the limit } f'(x) = \lim_{t \rightarrow x} \frac{f(t) - f(x)}{t - x} \text{ exists.}$$

- If f is differentiable at $x = p$, then f is continuous at $x = p$.
- If f is differentiable at $x = p$ and $g : f([a, b]) \rightarrow \mathbb{R}$ is differentiable at $x = f(p)$
 $\implies g \circ f$ is differentiable at $x = p$ and

$$(g \circ f)'(p) = g'(f(p))f'(p).$$

- (Fermat) If f is differentiable and has a local extremum at $x = a$, then $f'(a) = 0$.
- (Mean Value Theorem) If f is continuous on $[a, b]$ and differentiable on (a, b) , there exists $c \in (a, b)$ such that

$$f'(c) = \frac{f(b) - f(a)}{b - a}.$$

6. Integration

Given a bounded function $f : [a, b] \rightarrow \mathbb{R}$, a partition $P = \{a = x_0 < x_1 < \dots < x_n = b\}$ and a monotonically increasing function $\alpha : [a, b] \rightarrow \mathbb{R}$, define

$$U(P, f, \alpha) = \sum_{i=0}^{n-1} \sup_{x \in [x_i, x_{i+1}]} f(x) (\alpha(x_{i+1}) - \alpha(x_i))$$

$$L(P, f, \alpha) = \sum_{i=0}^{n-1} \inf_{x \in [x_i, x_{i+1}]} f(x) (\alpha(x_{i+1}) - \alpha(x_i))$$

We define upper integral and lower integral as follows:

$$\overline{\int_a^b} f d\alpha = \inf_{P \in \mathcal{P}[a, b]} U(P, f, \alpha) \quad \underline{\int_a^b} f d\alpha = \sup_{P \in \mathcal{P}[a, b]} L(P, f, \alpha).$$

f is Stieltjes integrable with respect to $\alpha \iff$

$$\forall \epsilon > 0, \exists P \in \mathcal{P}[a, b] \text{ such that } U(P, f, \alpha) - L(P, f, \alpha) < \epsilon.$$

Or equivalently, $\overline{\int_a^b} f d\alpha = \underline{\int_a^b} f d\alpha$. We write $f \in \mathcal{R}(\alpha)$.

Supplementary Material

F is a field for this section.

Definition. (Vector Space) A set V with addition $+: V \times V \rightarrow V$ and scalar multiplication $\cdot: F \times V \rightarrow V$ is a vector space over F if the following properties hold.

- (1) (Associativity of $+$) $u + (v + w) = (u + v) + w$ for all $v, w, u \in V$.
- (2) (Commutativity of $+$) $v + w = w + v$ for all $v, w \in V$.
- (3) (Identity of $+$) $\exists 0_V \in V$ such that $v + 0 = 0 + v = v$ for all $v \in V$.
- (4) (Inverse of $+$) For each $v \in V$, $\exists x \in V$ such that $v + x = x + v = 0_V$.
- (5) (Identity of \cdot) $1v = v$ for $v \in V$, where $1 \in F$ is the multiplicative identity in F .
- (6) (Distributive Property of \cdot w.r.t. Vector $+$) For $a \in F$ and $v, w \in V$, $a(v + w) = av + aw$.
- (7) (Distributive Property of \cdot w.r.t. Field $+$) For $a, b \in F$ and $v \in V$, $(a + b)v = av + bv$.
- (8) (Compatibility of \cdot w.r.t. $+$) $a(bv) = (ab)v$ for $a, b \in F$, $v \in V$.

We write $V = (V, +, \cdot)$.

Definition. (Normed Vector Space) A vector space V with a norm $\|\cdot\|: V \rightarrow \mathbb{R}$ is a normed vector space if the following properties hold.

- (1) $\|v\| \geq 0$ for all $v \in V$.
- (2) $\|v\| = 0 \iff v = 0$.
- (3) For all $\alpha \in F$ and $v \in V$, $\|\alpha v\| = |\alpha| \|v\|$.
- (4) (Triangle Inequality) For all $v, w \in V$, $\|v + w\| \leq \|v\| + \|w\|$.

For inner product spaces, $F = \mathbb{C}$ or $F = \mathbb{R}$.

Definition. (Inner Product Space) A vector space V with an inner product $\langle \cdot, \cdot \rangle: V \times V \rightarrow F$ is an inner product space if the following properties hold.

- (1) (Linearity in the first argument) For $x, y, z \in V$ and $a, b \in F$, $\langle ax + by, z \rangle = a \langle x, z \rangle + b \langle y, z \rangle$.
- (2) (Conjugate Symmetry) For $x, y \in V$, $\langle x, y \rangle = \overline{\langle y, x \rangle}$.
- (3) (Positive Definiteness) If $0 \neq x \in V$, $\langle x, x \rangle > 0$.

Remark. An inner product can induce a norm by $\|v\| = \sqrt{\langle v, v \rangle}$. With norm as the distance metric, the following holds.

$$\text{Inner Product Space} \implies \text{Normed Vector Space} \implies \text{Metric Space}$$

If the inner product space is complete with respect to the distance metric, it is said to be a Hilbert space.

September 8th, 2022 (Practice)

미분가능성이 잘 보존되지 않는다.

Example. $f_n(x) = \frac{\sin nx}{n}$. Converges to $f(x) = 0$ uniformly, but not differentiable.

$$f'_n(x) = \cos nx \neq f'(x) = 0$$

반례를 생각하는 방법: target limit function을 먼저 생각하고 개로 수렴하는 함수열을 잡는다.

Example. Consider a triangular pulse

$$f_n(x) = \begin{cases} n^2x & (0 \leq x \leq \frac{1}{n}) \\ -n^2x + 2n & (\frac{1}{n} \leq x \leq \frac{2}{n}) \end{cases}.$$

Converges pointwise, but not the convergence is not uniform.

Example. $f_n : X \subseteq \mathbb{R} \rightarrow \mathbb{R}$. Suppose $f_n \xrightarrow{u} f$. Then if f_n is increasing, f is also increasing.

Proof. (Contradiction) Suppose f is not increasing...!

Example. $f_n : X \rightarrow \mathbb{R}$. Suppose $f_n \xrightarrow{u} f$. If f_n has a local maxima at $x = 0$, f need not have a local maxima at $x = 0$. Consider

$$f_n(x) = \begin{cases} 0 & \left(x < \frac{1}{n} \right) \\ x - \frac{1}{n} & \left(x \geq \frac{1}{n} \right) \end{cases} \rightarrow f(x) = \begin{cases} 0 & (x < 0) \\ x & (x \geq 0) \end{cases}.$$

Then each f_n has a local maximum at $x = 0$, but $f(x)$ has a local minimum at $x = 0$.

Problem 7.3 Product of uniformly convergent sequence of functions need not converge uniformly.

Proof. Let $f_n(x) = \frac{1}{n}$, $g(x) = g_n(x) = x$. Then

$$f_n g_n - f g = \frac{x}{n},$$

which does not converge uniformly.

Theorem 7.11 (Cases with ∞) Theorem 7.11 also holds when

$$\lim_{x \rightarrow a} f_n(x) = \pm\infty, \quad \lim_{x \rightarrow \pm\infty} f_n(x) = A_n.$$

Proof. Consider a bijective, increasing, continuous function $g : (-1, 1) \rightarrow (-\infty, \infty)$, $g'(x) \geq$

1.

($a = \infty$ case) Then $x \rightarrow \infty$ with respect to f is equivalent to $x \rightarrow 1^-$ with respect to $f \circ g$. Observe that

$$\sup_{x \in (-1,1)} |f_n(g(x)) - f(g(x))| = \sup_{x \in \mathbb{R}} |f_n(x) - f(x)|,$$

thus $h_n = f_n \circ g$ will converge uniformly to $h = f \circ g$.

($\lim f_n(x) = \infty$ case) Similarly, consider $g^{-1} \circ f_n$ and $g^{-1} \circ f$. Then $\lim_{x \rightarrow a} g^{-1} \circ f_n = 1$. Now we show uniform convergence.

$$\lim_{n \rightarrow \infty} \sup_{x \in E} |g^{-1}(f_n(x)) - g^{-1}(f(x))| \leq \lim_{n \rightarrow \infty} \sup_{x \in E} |f_n(x) - f(x)| \cdot \sup_{x \in E} |(g^{-1})'(x)| \rightarrow 0$$

Example. $f_n : X \rightarrow Y$, $A_1, \dots, A_k \subseteq X$, $f_n \xrightarrow{u} f$ on $A_i \implies f_n \xrightarrow{u} f$ on $\bigcup A_i$.

Problem 7.4 Examine the function

$$f(x) = \sum_{n=1}^{\infty} \frac{1}{1+n^2x}.$$

Proof. We do not consider $x = -1/n^2$ for some $n \in \mathbb{N}$.

(Absolute Convergence) For $x \neq 0$, take large enough $N \in \mathbb{N}$ such that

$$\sum_{n=N}^{\infty} \left| \frac{1}{1+n^2x} \right| = \sum_{n=N}^{\infty} \left| \frac{1}{n^2x \left(1 + \frac{1}{n^2x}\right)} \right| \leq \sum_{n=N}^{\infty} \frac{1}{0.9n^2x} < \infty.$$

(Uniform Convergence) For $[k, \infty)$ ($k > 0$),

$$\sum_{n=m}^{\infty} \left| \frac{1}{1+n^2x} \right| \leq \sum_{n=m}^{\infty} \left| \frac{1}{n^2x} \right| \leq \frac{1}{k} \sum_{n=m}^{\infty} \frac{1}{n^2},$$

thus f converges uniformly on $[k, \infty)$. Now for $(-\infty, k]$ ($k < 0$),

$$\frac{1}{xm^2} > -\frac{1}{2} \iff m > \sqrt{\frac{-2}{x}}$$

and now we can choose m so that

$$\sum_{n=m}^{\infty} \left| \frac{1}{1+n^2x} \right| \leq \sum_{n=m}^{\infty} \left| \frac{1}{n^2x \cdot (1/2)} \right| \leq \frac{2}{|k|} \sum_{n=m}^{\infty} \frac{1}{n^2}.$$

Thus f also converges uniformly on $(-\infty, k]$. Now how about $(-\infty, 0) \cup (0, \infty)$? Suppose the

series converges uniformly. Then for $\epsilon = 1$, $\forall N \in \mathbb{N}$ such that

$$\left| \sum_{n=N}^{\infty} \frac{1}{1+n^2x} \right| < 1.$$

As $x \rightarrow 0^+$, $\frac{1}{1+N^2x} + \frac{1}{1+(N+1)^2x} \rightarrow 2$. Thus does not converge uniformly.

\therefore Converges uniformly on $(-\infty, -k] \cup [k, \infty)$, ($k > 0$).

(Continuity) Follows directly from uniform convergence. $(-\infty, -k] \cup [k, \infty)$.

(Boundedness) No.

Problem 7.12 Since $|f| \leq g$,

$$\int_a^b f \, dx = \int_a^b \frac{|f|+f}{2} \, dx - \int_a^b \frac{|f|-f}{2} \, dx.$$

Since $\int_0^\infty g \, dx < \infty$, (bounded) we can set $a \rightarrow 0$, $b \rightarrow \infty$.

For all $\epsilon > 0$, choose $[a, b]$ such that

$$\left| \int_0^\infty f \, dx - \int_a^b f \, dx \right| < \epsilon \text{ and } \left| \int_0^\infty g \, dx - \int_a^b g \, dx \right| < \epsilon.$$

by uniform continuity, $\exists N \in \mathbb{N}$ such that $n \geq N$ then $\left| \int_a^b f_n \, dx - \int_a^b f \, dx \right| < \epsilon$.

Therefore,

$$\left| \int_0^\infty f_n \, dx - \int_0^\infty f \, dx \right| < 3\epsilon$$

and the theorem is proven.

September 15th, 2022 (Practice)

Uniform continuity는 하나의 함수에 대해서 하는 이야기이고, equicontinuity는 여러 함수에 대해서 하는 이야기입니다. 둘 다 continuity의 확장입니다.

Definition. (고른연속) $f : X \rightarrow Y$ 가 **고른연속**이다. \iff

$$\forall \epsilon > 0, \exists \delta > 0 \text{ such that } d_X(x, y) < \delta \implies d_Y(f(x), f(y)) < \epsilon.$$

직관적으로는 “함수의 기울기가 finite하다”라고 이해할 수 있습니다. 물론 미분가능하지 않으면 기울기를 생각한다는게 웃기긴 하지만... 미분은 불가능 하더라도

$$\sup \left\{ \left| \frac{f(x) - f(y)}{x - y} \right| : x, y \in X, x \neq y \right\}$$

를 생각해 볼 수는 있겠죠.

Definition. (동등연속) Family of functions $\mathcal{F} = \{f_\alpha\}_{\alpha \in I}$ 가 **동등연속**이다. \iff

$$\forall \epsilon > 0, \exists \delta > 0 \text{ such that } d_X(x, y) < \delta \implies d_Y(f_\alpha(x), f_\alpha(y)) < \epsilon \text{ for all } \alpha \in I.$$

동등연속이 아니다? 그렇다면 $\left| \frac{f_\alpha(x) - f_\alpha(y)}{x - y} \right|$ 를 원하는 만큼 크게 할 수 있다. 단, 기울기가 발산한다고 해서 동등연속인지 아닌지는 확인해봐야 한다.

Example. (f_n) where $f_n(x) = nx$ is not equicontinuous.

Problem 7.10 $\{x\}$ denotes the fractional part of x .

$$f(x) = \sum_{n=1}^{\infty} \frac{\{nx\}}{n^2}$$

$f(x)$ converges uniformly by the M -test. 따라서 함수항급수의 부분합이 리만적분 가능한지 확인하면 된다. 닫힌 구간에서는 불연속점이 유한개이므로, 부분합은 당연히 리만적분 가능하고 이에 따라 f 도 리만적분 가능하다.

불연속점을 찾기 위해서는 각 항이 어디서 불연속인지 찾으면 되는데,

$$A_k = \left\{ \frac{b}{a} : a, b \in \mathbb{Z}, 1 \leq a \leq k \right\}$$

로 정의하면, f_k 는 $\mathbb{R} \setminus A_k$ 에서 연속일 것이다. 따라서 $\mathbb{R} \setminus \mathbb{Q}$ 에서도 연속이고, f 가 $\mathbb{R} \setminus \mathbb{Q}$ 에서 연속이다.

기약분수 $x = \frac{q}{p}$ 를 고정하자. ($p \geq 1$) 그러면 x 가 기약분수이므로

$$x \in A_p, A_{2p}, A_{3p}, \dots$$

일 것이다. 이제 연속인지 살펴보면,

$$\lim_{h \rightarrow 0^+} (f_k(x+h) - f_k(x-h)) = \sum_{n=1}^k \lim_{h \rightarrow 0^+} \left(\frac{\{n(x+h)\} - \{n(x-h)\}}{n^2} \right) \quad (*)$$

이다. 만약 $n = pl$ ($l \in \mathbb{Z}$) 이라고 하면, (*)의 분자는

$$\sum_{\substack{p|n \\ 1 \leq n \leq k}} \frac{-1}{n^2}$$

이 된다. 만약 f 가 연속이었다면, $k \rightarrow \infty$ 일 때 $(*) \rightarrow 0$ 이었어야 한다. 하지만 그렇지 않으므로, 불연속이다. \mathbb{Q} 가 countably dense 임은 이미 알고 있다.

Problem 7.14 (Space-Filling Curve) Define $0 \leq f(t) \leq 1$, $f(t) = f(t+2)$

$$f(t) = \begin{cases} 0 & (t \in [0, \frac{1}{3}]) \\ 1 & (t \in [\frac{2}{3}, 1]) \end{cases}.$$

Also define, $\Phi(t) = (x(t), y(t))$ where

$$x(t) = \sum_{n=1}^{\infty} 2^{-n} f(3^{2n-1}t), \quad y(t) = \sum_{n=1}^{\infty} 2^{-n} f(3^{2n}t).$$

우선 M -test에 의해 $x(t), y(t)$ 가 고르게 수렴함을 안다. f 가 연속이므로, Φ 도 연속이다.

칸토어 집합 K 은 compact, perfect, 길이가 양수인 구간을 포함하지 않음. 하지만 $\mu(K) > 0$. 각 원소를 3진수로 썼을 때 모든 자리수가 0 또는 2.

Problem 7.18 F_n 이 pointwise bounded 이고 equicontinuous임을 보이면 끝!

Problem 7.23 귀납법.