MATH 20410 (Analysis in $\mathbb{R}^n$ II – Accelerated) Notes

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February 6, 2022

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Chapter 6

The Riemann-Stieltjes Integral

6.1 Notes

1/28:

- Plan:
  1. Finish up Fundamental Theorem of Calculus proof.
  2. Basic consequences.
  3. Rectifiable curves.
- Recall that we're given $f : [a, b] \to \mathbb{R}$ continuous, $f : [a, b] \to \mathbb{R}$, and $x \mapsto \int_a^x f(t)\,\mathrm{d}t$.
- Goal: Show $F'(x_0) = f(x_0)$.
  - WTS: Find δ such that $|x - x_0| < \delta$ implies

$$
\begin{aligned}
\left|\frac{1}{x - x_0}\int_{x_0}^{x} f(t)\,\mathrm{d}t - f(x_0)\right| &= \left|\frac{1}{x - x_0}\int_{x_0}^{x} f(t)\,\mathrm{d}t - \frac{1}{x - x_0}\int_{x_0}^{x} f(x_0)\,\mathrm{d}t\right| \\
&= \frac{1}{|x - x_0|}\left|\int_{x_0}^{x} (f(t) - f(x_0))\,\mathrm{d}t\right| \\
&\leq \frac{1}{|x - x_0|}\int_{x_0}^{x} |f(t) - f(x_0)|\,\mathrm{d}t \\
&< \epsilon
\end{aligned}
$$

  - Since f is continuous, there exists δ such that if $|x - x_0| < \delta$, then $|f(x) - f(x_0)| < \epsilon$.
  - Now

$$
\begin{aligned}
\frac{1}{|x - x_0|}\int_{x_0}^{x} |f(t) - f(x_0)|\,\mathrm{d}t &< \frac{1}{|x - x_0|}\int_{x_0}^{x} \epsilon\,\mathrm{d}t \\
&= \epsilon
\end{aligned}
$$

- Applications:
  1. Theorem (MVT for integration): $f : [a, b] \to \mathbb{R}$ continuous, then there exists $x_0 \in [a, b]$ such that

$$
f(x_0) = \frac{1}{b - a}\int_a^b f(x)\,\mathrm{d}x
$$

     - Apply MVT to $F(x) = \int_a^x f(t)\,\mathrm{d}t$. Then

$$
F'(x_0) = f(x_0) = \frac{F(b) - F(a)}{b - a}
$$

       as desired.

2. Theorem (Integration by parts): Let $F, G : [a, b] \to \mathbb{R}$ be differentiable with $F' = f$, $G' = g$ and with f and g both integrable. Then

$$\int_a^b Fg = F(b)G(b) - F(a)G(a) - \int_a^b fG$$

   - Just use the product rule plus the FTC to prove.
   - We have

$$\begin{aligned}\int_a^b (FG)' &= \int_a^b fG + \int_a^b Fg \\ F(b)G(b) - F(a)G(a) &= \int_a^b fG + \int_a^b Fg \\ \int_a^b Fg &= F(b)G(b) - F(a)G(a) - \int_a^b fG\end{aligned}$$

3. Theorem (u-substitution).
   - Follows similarly from the chain rule and FTC.

- Integration of vector-valued functions.
- If $f : [a, b] \to \mathbb{R}^k$, we define $\int_a^b f$ by

$$\int_a^b f = \left(\int_a^b f_1, \dots, \int_a^b f_k \right)$$

- Alternatively, you can define $\int_a^b f$ using P, $U(f, P)$, $L(f, P)$, etc. and then prove that the integral exists iff all f_i are integrable and in this case the above definition holds.
- Rectifiable curves: Let $\gamma : [a, b] \to \mathbb{R}^k$ be a continuous function.
- Plan: Define the length of γ and show that we can compute it with an integral.
  - Idea: For polygonal paths, we know how to define length. So let's approximate γ by polygons and take a limit.
  - Ref: Given a partition P, then define the length of γ with respect to P as $\Lambda(\gamma, P)$. Let the length of γ be $\Lambda(\gamma) = \sup_P \Lambda(\gamma, P)$ if this limit exists in this case, we call γ **rectifiable**.
- Fractals are not rectifiable — their length diverges.
- Theorem: Suppose γ is continuously differentiable (i.e., γ is differentiable and γ' is continuous). Then γ si rectifiable and

$$\Lambda(\gamma) = \int_a^b |\gamma'(t)| \,\mathrm{d}t$$

  - Notice: If $P \leq P'$, then $\Lambda(\gamma, P) \leq \Lambda(\gamma, P')$. (Prove with triangle inequality.)
  - WTS: For all partitions P, $\Lambda(\gamma, P) \leq \int_a^b |\gamma'(t)| \,\mathrm{d}t$ and thus $\Lambda(\gamma) \leq \int_a^b |\gamma'(t)| \,\mathrm{d}t$.
  - We have that

$$\begin{aligned}\Lambda(\gamma, P) &= \sum_{i=1}^n |\gamma(x_i) - \gamma(x_{i-1}) \\ &= \sum_{i=1}^n \left| \int_{x_{i-1}}^{x_i} \gamma'(t) \,\mathrm{d}t \right| \\ &\leq \sum_{i=1}^n \int_{x_{i-1}}^{x_i} |\gamma'(t)| \,\mathrm{d}t \\ &= \int_a^b |\gamma'(t)| \,\mathrm{d}t\end{aligned}$$

- Catch up.
  - I should make up PSets 1-2.
  - Exams have less than Rudin-strength problems.
  - Exams are mostly true/false (and of that, mostly false, provide a counterexample).

6.2 Exam 1 Additional Topics

- A continuous function that is not always differentiable.

$$f(x) = |x|$$

- A differentiable function with a discontinuous derivative.

$$f(x) = x^2 \sin \frac{1}{x}$$

- A vector-valued function that doesn't satisfy the MVT.

$$\mathbf{f}(x) = \mathrm{e}^{ix}$$

  - Between 0 and 2π.
- A pair of vector-valued functions that don't satisfy L'Hôpital's rule.

$$f(x) = x \qquad\qquad g(x) = x + x^2 \mathrm{e}^{i/x^2}$$

Chapter 7

Sequences and Series of Functions

7.1 Notes

1/31:

- Midterm on differentiation and integration, and a bit of stuff from this week.
- Plan:
  - Talk about sequences of functions, all with the same domain and range, converging.
  - Address what properties of f_n remain in the limit (e.g., continuity, differentiability, integrability).
    - The answer depends on what we mean by "convergence."
    - $f_n \to f$ pointwise implies basically nothing.
    - $f_n \to f$ uniformly implies that basically everything works out nicely.
- We'll restrict ourselves to real functions because those have all the properties (integrability, differentiability, etc.) that we care about.
- **Pointwise** (convergent sequence $\{f_n\}$ to f): A sequence of functions $\{f_n\}$ such that for all $x \in X$, the sequence $\{f_n(x)\}$ converges to $f(x)$, where $f_n : X \to \mathbb{R}$ for all $n \in \mathbb{N}$ and $f : X \to \mathbb{R}$. *Denoted by* $f_n \to f$.
- Bad functions.
  - Consider $f_n : [0,1] \to \mathbb{R}$ defined by $x \mapsto x^n$. Each f_n is continuous, but f is not (zero everywhere except $f(1) = 1$)[1].
  - Consider $f_n : \mathbb{R} \to \mathbb{R}$ defined by $f_n(x) = x^2/(1+x^2)^n$, and $f(x) = \sum_{n=0}^{\infty} f_n(x)$. As a geometric series, $f(x) = 1 + x^2$ when $x \neq 0$ but $f(0) = 0$. Thus, the limit exists but is not continuous once again.
  - Consider $f_m : \mathbb{R} \to \mathbb{R}$ defined by $x \mapsto \lim_{n\to\infty} \cos^{2n}(m!\pi x)$. Each f_m is integrable, but the limit f is the function that's 1 for rationals and zero for irrationals. In particular, f is not integrable.
    - We take even powers of the cosine to make it always positive.
    - We use $\cos^2(x)$ just because its always between $[0,1]$, and we know when it is equal to 1.
    - In particular, $\cos^2(\pi x)$ is equal to 1 at every integer, $\cos^2(2\pi x)$ is equal to 1 at every half integer. $\cos^2(6\pi x)$ is equal to 1 at every one-sixth of an integer.
    - Then raising it to the n^{th} power just makes it spiky.
- Aside: Interchanging limits.
  - If all f_n are continuous, then $\lim_{x\to x_0} f_n(x) = f_n(x_0)$.

[1] Questions that require counterexamples like this could show up on the midterm!

  - The question "is f continuous" is equivalent to being able to interchange limits:

$$\lim_{x\to x_0}\lim_{n\to\infty} f_n(x) = f(x_0) = \lim_{n\to\infty}\lim_{x\to x_0} f_n(x)$$

  - Sequence example showing we need to be careful interchanging limits: $s_{n,m} = m/(m+n)$.

- All of this pathology goes away with the right definition, though.
- **Uniformly** (convergent sequence $\{f_n\}$ to f): A sequence of functions $\{f_n\}$ such that for all $\epsilon > 0$, there exists an N such that if $n \geq N$, then $|f_n(x) - f(x)| < \epsilon$ for all $x \in X$, where $f_n : X \to \mathbb{R}$ for all $n \in \mathbb{N}$ and $f : X \to \mathbb{R}$.
- Proposition (Cauchy criterion for uniform convergence): $f_n \to f$ uniformly iff for all $\epsilon > 0$, there exists N such that for all $m, n \geq N$ and for all $x \in X$, $|f_n(x) - f_m(x)| < \epsilon$.
  - Forward direction: Let $\epsilon > 0$. Suppose $f_n \to f$ uniformly. Choose N such that the functions are within $\epsilon/2$. Then

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

2/2:
- Office hours tomorrow 4-5 PM.
- Plan:
  1. More on uniform convergence.
     - Limit of continuous functions is continuous.
     - Limit of the integral of functions is the integral of the limit.
  2. $\mathcal{C}(X)$ perspectives on uniform convergence.
- Corollary (Weierstraß M-test): If there exist constants $M_n \in \mathbb{R}$ such that $|f_n(x)| \leq M_n$ for all x and $\sum_{n=1}^{\infty} M_n$ converges, then $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly.
- Theorem: $f_n : X \to \mathbb{R}$, f_n continuous at $x_0 \in X$ for all n, and $f_n \to f$ uniformly imply f continuous at x_0.
  - Idea:
    - "$\epsilon/3$ trick": Find δ such that if $|x - x_0| < \delta$, then

$$|f(x) - f(x_0)| \leq |f(x) - f_N(x)| + |f_N(x) - f_N(x_0)| + |f_N(x_0) - f(x_0)| < \frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3} = \epsilon$$

  - Proof:
    - $f_n \to f$ uniformly implies there exists $N \in \mathbb{N}$ such that $|f_N(x) - f(x)| < \epsilon/3$ for all $x \in X$.
    - f_N continuous at x_0: There exists δ such that if $d(x, x_0) < \delta$, then $|f_N(x) - f_N(x_0)| < \epsilon/3$.
    - Thus, by the $\epsilon/3$ trick, we have the continuity of f.
- Defining a norm on $\mathcal{C}(X)$.

$$\|f\| = \sup_{x\in X} |f(x)|$$

  - This makes $\mathcal{C}(X)$ into a vector space.
  - We can now define our metric $d(f, g)$ by $d(f, g) = \|f - g\|$.
- $f_n \to f \iff f$ is bounded.
  - $f_n \to f$ uniformly $\iff \lim_{n\to\infty} \sup |f_n(x) - f(x)| = 0 \iff f_n \to f$ is $\mathcal{C}(X)$.
- Corollary to the Weierstraß M-test: $\mathcal{C}(X)$ is complete (i.e., all uniformly Cauchy sequences converge).

  - Assume $\{f_n\}$ is Cauchy. Then by the Cauchy criterion for uniform convergence, f_n converges uniformly to some f. But this f must be continuous, too, meaning $f \in \mathcal{C}(X)$.

2/4:

- Plan.
  1. $\int \lim f_n = \lim \int f_n$.
  2. $\mathrm{d}x \lim f_n = \lim \mathrm{d}x\, f_n$.
  3. Definitions: Pointwise/uniform boundedness, equicontinuity.
- Theorem: $f_n : [a,b] \to \mathbb{R}$ integrable and $f_n \to f$ uniformly implies f is integrable and

$$\int_a^b f = \lim_{n\to\infty} \int_a^b f_n$$

  - Plan:
    1. Show f is integrable.
    2. Show $\int f = \lim \int f_n$.
  - Proof:
    - Let $\epsilon_n = \sup_{x\in[a,b]} |f(x) - f_n(x)|$.
    - Since $f_n \to f$ uniformly, $\epsilon_n \to 0$ as $n \to \infty$.
    - By definition, $f_n - \epsilon_n \le f \le f_n + \epsilon_n$.
    - Thus, by Theorems 6.4 and 6.5,

$$\int_a^b (f_n - \epsilon_n) = \underline{\int} (f_n - \epsilon_n) \le \underline{\int} f \le \bar{f} \le \int_a^b (f_n + \epsilon_n)$$

    - It follows since

$$0 \le \overline{\int} f - \underline{\int} f \le \int_a^b (f_n + \epsilon_n) - \int_a^b (f_n - \epsilon_n) = (b-a)...$$

      that f is integrable.
    - Hence,

$$\begin{aligned} \int_a^b (f_n - \epsilon_n) \le \int_a^b f \le \int_a^b (f_n - \epsilon_n) \\ \left| \int_a^b f_n - \int_a^b f \right| \le \epsilon_n \\ \lim_{n\to\infty} \int_a^b f_n = \int_a^b f \end{aligned}$$

- Theorem: $f_n : [a,b] \to \mathbb{R}$, each f_n differentiable, $f_n \to f$ pointwise, and $(f_n)' \to g$ uniformly implies that f is differentiable and $f' = g$.
  - Note that you can do better: Substituting $f_n(x_0)$ converging for some $x_0 \in [a,b]$ for $f_n \to f$ pointwise still implies the desired result.
  - Idea: We use the $\epsilon/3$ trick; 2/3 will be easy and 1/3 will be tricky.
  - Goal: We want

$$\left| \frac{f(x) - f(x_0)}{x - x_0} - g(x_0) \right| < \epsilon$$

    for some δ with $0 < |x - x_0| < \delta$. We will show that

$$\begin{aligned} &\left| \frac{f(x) - f(x_0)}{x - x_0} - \frac{f_N(x) - f_N(x_0)}{x - x_0} + \frac{f_N(x) - f_N(x_0)}{x - x_0} - f_N'(x_0) + f_N'(x_0) - g(x_0) \right| \\ \le &\left| \frac{f(x) - f(x_0)}{x - x_0} - \frac{f_N(x) - f_N(x_0)}{x - x_0} \right| + \left| \frac{f_N(x) - f_N(x_0)}{x - x_0} - f_N'(x_0) \right| + |f_N'(x_0) - g(x_0)| \end{aligned}$$

- For the middle inequality, use Chapter 5, Exercise 8.
- For the right inequality, use the uniform convergence condition.
- For the left inequality, it will suffice to show the Cauchy condition

$$\left|\frac{f_n(x)-f_n(x_0)}{x-x_0}-\frac{f_m(x)-f_m(x_0)}{x-x_0}\right|<\frac{\epsilon}{3}$$

  so, noting that the left term above is equal to

$$\left|\frac{[f_n(x)-f_m(x)]-[f_n(x_0)-f_m(x_0)]}{x-x_0}\right|$$

  which is equal to $|f_n'(c)-f_m'(c)|$ by the MVT, from which we can apply the Cauchy form of the uniform convergence of $(f_n)'$ condition.

- **Pointwise bounded** ($\{f_n\}$): A sequence of real functions $\{f_n\}$ such that for all $x \in X$, there exists $M_x \in \mathbb{R}$ such that $|f_n(x)| \leq M_x$ for all $n \in \mathbb{N}$.
- **Uniformly bounded** ($\{f_n\}$): A sequence of real functions $\{f_n\}$ for which there exists $M \in \mathbb{R}$ such that for all $x \in X$ and $n \in \mathbb{N}$, $|f_n(x)| \leq M$.
- Proposition: $f_n : E \to \mathbb{R}$, $\{f_n\}$ is pointwise bounded, and E is countable implies there is a subsequence $\{f_{n_k}\}$ that converges pointwise.
  - Enumerate $E = \{x_1, x_2, \dots\}$.
  - Then since $\{f_n(x_m)\}$ is bounded for all m by hypothesis, it always has a convergent subsequence.
  - The claim is if you look at the sequence of diagonal functions, it is such a subsequence, i.e., if $f_1(x_1)$ is the first term for x_1, $f_3(x_2)$ is the second term for x_2, $f_{11}(x_3)$ is the third term for x_3, and so on, $f_1, f_3, f_{11}, \dots$ is such a subsequence.