

MATH 131BH (Real Analysis)

April 29, 2022

- 1 **3.28 Monday Week 1: Intro to the course. Review of material covered in 131AH: foundations (definition and constructions of naturals and reals), metric space convergence, continuity.**
- 2 **3.30 Wednesday Week 1: Limit of a function: definition and alternative formulations via images of balls and sequential characterization. Limit on a set, left and right limits for functions on \mathbb{R} . Discontinuities of first and second kind. Monotone functions have no discontinuities of second kind.**

Limits of functions

Recall: $f: X \rightarrow Y$ is said to be **continuous** at $x \in X$ if

$$\forall \varepsilon > 0 \exists \delta > 0 \forall z \in X : \rho_X(x, z) < \delta \Rightarrow \rho_Y(f(z), f(x)) < \varepsilon.$$

Alternatives:

- $f(B_X(x, \delta)) \subseteq B_Y(f(x), \varepsilon)$;
- $\forall \{x_n\}_{n \in \mathbb{N}} \in X^{\mathbb{N}} : x_n \rightarrow x \Rightarrow f(x_n) \rightarrow f(x)$.

A function $f: X \rightarrow Y$ is **continuous** if

$$\forall x \in X : f \text{ is continuous at } x,$$

or, alternatively,

$$\forall O \subseteq Y \text{ open} : f^{-1}(O) \text{ open}.$$

Definition 2.1

A function $f: X \rightarrow Y$ **has limit** $y \in Y$ **at** $x \in X$, notation $\lim_{z \rightarrow x} f(z) = y$, if

$$\forall \varepsilon > 0 \exists \delta > 0 \forall z \in X : 0 < \rho_X(x, z) < \delta \Rightarrow \rho_Y(f(z), y) < \varepsilon.$$

Alternatives:

- $f(B_X(x, \delta) \setminus \{x\}) \subseteq B_Y(y, \varepsilon)$;
- $\forall \{x_n\}_{n \in \mathbb{N}} \in X^{\mathbb{N}} : (\forall n \in \mathbb{N} : x_n \neq x) \wedge x_n \rightarrow x \Rightarrow f(x_n) \rightarrow y$;
- $g(z) := \begin{cases} f(z) & z \neq x \\ y & z = x \end{cases}$ is continuous at x .

Definition 2.2

f has a **removable discontinuity** at x if $\lim_{z \rightarrow x} f(z)$ exists but $\neq f(x)$.

Definition 2.3

Let $A \subseteq X$ be nonempty, $x \in \overline{A}$ be not an isolated point. Then $\lim_{z \rightarrow x} f(z) = \lim_{z \rightarrow x} f_A(z)$ where f_A is the restriction of f to A .

Definition 2.4

For $f: \mathbb{R} \rightarrow \mathbb{R}$, let $x \in \overline{\text{Dom}(f)}$ be such that $\text{Dom}(f) \cap (x, \infty) \neq \emptyset$ and $\text{Dom}(f) \cap (-\infty, x) \neq \emptyset$. Then $\lim_{z \rightarrow x^+} f(z) := \lim_{z \rightarrow x, z \in \text{Dom}(f) \cap (x, \infty)} f(z)$ and $\lim_{z \rightarrow x^-} f(z) := \lim_{z \rightarrow x, z \in \text{Dom}(f) \cap (-\infty, x)} f(z)$ are the **right / left limits of f at x** .

Alternative notation: $f(x^+)$, $f(x^-)$.

Example 2.5.

$$f(x) = \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}$$

has no right or left limits.

Example 2.6.

$$f(x) = \begin{cases} \frac{1}{n+1} & x = q_n \text{ where } \{q_n\}_{n \in \mathbb{N}} \text{ enumerates } \mathbb{Q} \\ 0 & x \notin \mathbb{Q}. \end{cases}$$

Then $\forall x \notin \mathbb{Q} : \lim_{z \rightarrow x} f(z) = 0$ so f is continuous on $\mathbb{R} \setminus \mathbb{Q}$, and $\forall x \in \mathbb{Q} : \lim_{z \rightarrow x} f(z) = 0$ but f is not continuous at x .

Lemma 2.7

$$\forall r > 0 \forall \varepsilon > 0 : \{x \in \mathbb{R} : |x| < r \wedge |f(x)| > \varepsilon\} \text{ finite} \Rightarrow \forall x \in \mathbb{R} : \lim_{z \rightarrow x} f(z) = 0.$$

Definition 2.8

A function $f: \mathbb{R} \rightarrow \mathbb{R}$ has a **discontinuity of**

- **first kind** at x if $f(x^+)$ and $f(x^-)$ exist but are not both equal to $f(x)$;
- **second kind** at x if one or both of $f(x^+)$ and $f(x^-)$ don't exist.

Example 2.9.

$$f(x) := \begin{cases} (-1)^n & x = \frac{1}{n+1}, n \in \mathbb{N} \\ \text{linear} & x \in (0, \infty) \setminus \left\{ \frac{1}{n+1} : n \in \mathbb{N} \right\} \\ 0 & x \leq 0. \end{cases}$$

This function has a discontinuity of second kind at 0.

Lemma 2.10

Let $f: \mathbb{R} \rightarrow \mathbb{R}$ ($\text{Dom}(f) = \mathbb{R}$) be monotone. Then $\forall x \in \mathbb{R} : f(x^+), f(x^-)$ exist and so f has no discontinuities of second kind.

Proof. Let $x \in \mathbb{R}$ and assume f is nondecreasing. We claim that $\lim_{z \rightarrow x^+} f(z) = \inf \{f(z) : z > x\} =: L$.

Indeed, $\forall z > x : f(z) \geq f(x)$, so $L \geq f(x)$ and so $L \in \mathbb{R}$. Then $(\forall z > x : L \leq f(z)) \wedge (\forall \varepsilon > 0 \exists z_\varepsilon > x : f(z_\varepsilon) < L + \varepsilon)$. Let $\delta := z_\varepsilon - x$. Then $\forall z \in (x, x + \delta) : f(z) \leq f(z_\varepsilon) < L + \varepsilon$. Then $\forall z \in (x, x + \delta) : L \leq f(z) < L + \varepsilon$ and therefore $|f(z) - L| < \varepsilon$. Then $\lim_{z \rightarrow x^+} f(z) = L$. \square

3 3.31 Thursday Week 1: Monotone functions have only countably many discontinuities. Functions of bounded variation. Jordan decomposition theorem. Comments on uniqueness. Rectifiability of curves. Limsup and liminf of a function.

Limits of functions

Last time we showed that monotone functions have no discontinuities of second kind.

Lemma 3.1

Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be monotone. Then $\{x \in \mathbb{R} : f(x^+) \neq f(x^-)\}$ is countable.

Proof. Pick $k, m \in \mathbb{N}$ and let $A_{m,k} := \{x \in [-m, m] : |f(x^+) - f(x^-)| > \frac{1}{k+1}\}$. We claim that $A_{m,k}$ is finite.

Let $x_0 < x_1 < \dots < x_n$ be such that $\forall i \leq n : x_i \in A_{m,k}$. Assume (without loss of generality) that f is non-decreasing. Then

$$\begin{aligned} f(m+1) &\geq f(x_n^+) = f(x_0^+) + \sum_{i=1}^n (f(x_i^+) - f(x_{i-1}^+)) \\ &\geq f(m-1) + \sum_{i=1}^n (f(x_i^+) - f(x_i^-)) \\ &\geq f(-m+1) + \frac{n}{k+1}. \end{aligned} \tag{3.1}$$

Then $n \leq (k+1)$. Since $\{x \in \mathbb{R} : f(x^+) \neq f(x^-)\} = \bigcup_{k \in \mathbb{N}} \bigcup_{m \in \mathbb{N}} A_{m,k}$, we are done. \square

Q: Can these be generalized to other functions?

Definition 3.2

A **partition** Π of an interval $[a, b]$ is a sequence $\{t_i\}_{i=0}^n$ such that

$$a = t_0 < t_1 < \cdots < t_{n-1} < t_n = b.$$

Definition 3.3

Given $f: [a, b] \rightarrow \mathbb{R}$, its **total variation** on $[a, b]$

$$V(f, [a, b]) := \sup_{\Pi = \{t_i\}_{i=0}^n} \sum_{i=1}^n |f(t_i) - f(t_{i-1})|$$

where the supremum is over the partitions of $[a, b]$.

Definition 3.4

f is said to be of **bounded variation** on $[a, b]$ if $V(f, [a, b]) < \infty$.

Lemma 3.5

If $f: \mathbb{R} \rightarrow \mathbb{R}$ is of bounded variation on $[-m, m]$ for all $m \in \mathbb{N}$, then f has only discontinuities of first kind and the set $\{x \in \mathbb{R} : f(x^+) \neq f(x^-)\}$ is countable.

Theorem 3.6: Jordan decomposition (1881)

Let $f: [a, b] \rightarrow \mathbb{R}$ obey $V(f, [a, b]) < \infty$. Then $\exists h, g: [a, b] \rightarrow \mathbb{R}$ nondecreasing such that $\forall t \in [a, b] : f(t) = h(t) - g(t)$.

Proof. Define $h(t) := V(f, [a, t])$ and $g(t) := V(f, [a, t]) - f(t)$. Note that $h(t) - g(t) = f(t)$.

We need to show that h and g are nondecreasing.

Let $a \leq t < t' \leq b$. Then for any partition Π of $[a, t]$, $\Pi' = \Pi \cup \{t'\}$ is a partition of $[a, t']$. Then

$$V(f, [a, t']) \geq \sum_{i=1}^m |f(t_i) - f(t_{i-1})| + |f(t') - f(t)|.$$

Taking supremum over Π gives

$$V(f, [a, t']) \geq V(f, [a, t]) + |f(t') - f(t)|.$$

Note that $|f(t') - f(t)| \geq 0$ and $|f(t') - f(t)| \geq f(t') - f(t)$. Then $h(t') \geq h(t)$ and $g(t') \geq g(t)$. □

The representation of $f = h - g$ is called a Jordan decomposition. This is not unique because a nondecreasing function can be added to both h and g .

However, there is a minimal decomposition $f = h_0 - g_0$ such that $g_0(a) = 0$ such that for any other Jordan decomposition $f = h - g$ we have $h - h_0, g - g_0$ nondecreasing. This is then *the* Jordan decomposition.

Rectifiability of curves

Definition 3.7

Let (X, ρ) be a metric space. A curve C is $\text{Ran}(f)$ for an $f: \mathbb{R} \rightarrow X$ continuous such that $\text{Dom}(f)$ is nonempty and connected. This f is called a **parametrization** of C .

Definition 3.8

Assuming $\text{Dom}(f) = [a, b]$, the **length of C** is

$$\ell(C) := \sup_{\Pi = \{t_i\}_{i=0}^n} \sum_{i=1}^n \rho(f(t_{i-1}), f(t_i)).$$

Definition 3.9

A curve is **rectifiable** if $\ell(C) < \infty$.

Definition 3.10

Let (X, ρ) be a metric space and $f: X \rightarrow \mathbb{R}$. Then

$$\limsup_{z \rightarrow x} f(z) := \inf_{\delta > 0} \sup_{z \in B(x, \delta) \setminus \{x\}} f(z)$$

and

$$\liminf_{z \rightarrow x} f(z) := \sup_{\delta > 0} \inf_{z \in B(x, \delta) \setminus \{x\}} f(z).$$

Lemma 3.11

$$\lim_{z \rightarrow x} f(z) \text{ exists in } \mathbb{R} \Leftrightarrow \limsup_{z \rightarrow x} f(z) = \liminf_{z \rightarrow x} f(z) \in \mathbb{R}.$$

4 4.1 Friday Week 1: Discussion

Definition 4.1

Let $(X, \rho_X), (Y, \rho_Y)$ be metric spaces, $E \subseteq X$, $f: E \rightarrow Y$, and $x \in \bar{E}$. Then $\lim_{t \rightarrow x} f(t) = \alpha$ is defined by

$$\forall \varepsilon > 0 \exists \delta > 0 : \forall x \in E \wedge 0 < \rho_X(t, x) < \delta \Rightarrow \rho_Y(f(t), \alpha) < \varepsilon.$$

Equivalently,

$$\forall \{t_n\}_{n \in \mathbb{N}} \in (E \setminus \{x\})^{\mathbb{N}} : t_n \rightarrow x \Rightarrow f(t_n) \rightarrow \alpha.$$

Note. f need not be defined at x .

Remark.

$$\limsup_{t \rightarrow x} f(t) := \inf_{\delta > 0} \sup_{t \in B(x, \delta) \setminus \{x\}} f(t) = \lim_{\delta \rightarrow 0} \sup_{t \in B(x, \delta) \setminus \{x\}} f(t).$$

\liminf is similarly defined.

Remark.

$$\limsup = \liminf \Rightarrow \lim \text{ exists.}$$

Discontinuities

Definition 4.2

Let $f: (a, b) \rightarrow \mathbb{R}$ be not continuous at x . Then f has a **discontinuity of first kind** at x if $f(x+)$ and $f(x-)$ both exist. Otherwise it is of **second kind**.

Remark. Discontinuities of first kind are also known as **simple discontinuities**. The cases include

- $f(x+) = f(x-) \neq f(x)$: **removable discontinuity**, and
- $f(x+) \neq f(x-)$: **jump discontinuity**.

Example 4.3.

$$f(x) = \begin{cases} \sin\left(\frac{1}{x}\right) & x \neq 0 \\ 0 & x = 0 \end{cases}$$

has a discontinuity of second kind at 0.

Example 4.4.

$$f(x) = \begin{cases} \frac{1}{q} & x = \frac{p}{q} \in \mathbb{Q} \\ 0 & x \in \mathbb{R} \setminus \mathbb{Q} \end{cases}$$

is continuous on $\mathbb{R} \setminus \mathbb{Q}$ and has discontinuities of first kind (removable) at every point in \mathbb{Q} .

Recall: A monotone function has no discontinuity of second kind and has at most countably many discontinuities of first kind. One can deduce this from the fact that the real line is a union of countably many open intervals (indexed by rationals).

Definition 4.5

A function $f: (a, b) \rightarrow \mathbb{R}$ is convex if

$$\forall x, y \in (a, b) : x \leq y \Rightarrow (\forall \lambda \in [0, 1] : f(\lambda x + (1 - \lambda)y)) \leq \lambda f(x) + (1 - \lambda)f(y).$$

In words, this means that for any interval, the secant line is above the graph.

5 4.4 Monday Week 2: Existence of limit is equivalent to equality and finiteness of limsup and liminf. Derivative of a real valued function of one real variable. Differentiability implies continuity. Connection with linear approximation. Sum and product rule, chain rule and inverse function rule. First-derivative test and discussion of important counterexamples.

Last time: $\lim_{z \rightarrow x} f(z)$, $\limsup_{z \rightarrow x} f(z) = \inf_{\delta > 0} \sup_{z \in B(x, \delta) \setminus \{x\}} f(z)$

Lemma 5.1

$$\lim_{z \rightarrow x} f(z) \text{ exists (in } \mathbb{R}) \Leftrightarrow \limsup_{z \rightarrow x} f(z) = \liminf_{z \rightarrow x} f(z) \in \mathbb{R}.$$

Proof. Both are equivalent:

$$\forall \varepsilon > 0 \exists \delta > 0 : 0 \leq \sup_{z \in B(x, \delta) \setminus \{x\}} f(z) - \inf_{z \in B(x, \delta) \setminus \{x\}} f(z) \leq 2\varepsilon.$$

□

Definition 5.2

$$\lim_{z \rightarrow x} f(z) = \begin{cases} +\infty & \limsup_{z \rightarrow x} f(z) = \liminf_{z \rightarrow x} f(z) = +\infty \\ -\infty & \limsup_{z \rightarrow x} f(z) = \liminf_{z \rightarrow x} f(z) = -\infty. \end{cases}$$

Note. This characterization works even outside \mathbb{R} -valued functions:

$$\lim_{z \rightarrow x} f(z) \text{ exists} \Leftrightarrow \lim_{\delta \rightarrow 0^+} \underbrace{\sup \{ \rho(f(z), f(u)) : z, u \in B(x, \delta) \setminus \{x\} \}}_{= \text{diam}(f(B(x, \delta) \setminus \{x\}))} = 0.$$

The derivative

Definition 5.3

Let $f : \mathbb{R} \rightarrow \mathbb{R}$, $x \in \text{int}(\text{Dom}(f))$. We say that f has **derivative** or is **differentiable at x** if

$$f'(x) := \lim_{z \rightarrow x} \frac{f(z) - f(x)}{z - x} \text{ exists in } \mathbb{R}.$$

We call $f'(x)$ (Lagrange notation) the **derivative at x** , alternative notation $\frac{df}{dx}$ (Leibniz notation).

Lemma 5.4

$$f'(x) \text{ exists} \Rightarrow f \text{ continuous at } x.$$

Proof. The existence of $f'(x)$ implies that $\exists \delta_0 > 0 \forall z \in \mathbb{R} : 0 < |z - x| < \delta_0 \Rightarrow \left| \frac{f(z) - f(x)}{z - x} \right| \leq 1 + |f'(x)|$. Then, choosing $\varepsilon > 0$ and letting $\delta := \frac{\varepsilon}{1 + |f'(x)|}$, we get

$$\forall z \in \mathbb{R} : 0 < |z - x| < \delta \Rightarrow |f(z) - f(x)| \leq (1 + |f'(x)|) |z - x| < (1 + |f'(x)|) \frac{\varepsilon}{1 + |f'(x)|} = \varepsilon.$$

Since $f(z) - f(x) = 0$ for $z = x$, we are done (in fact, we have shown that f is Lipschitz continuous). \square

Another way to write existence of $f'(x)$:

$$f(z) - f(x) = (f'(x) + u_x(z))(z - x)$$

where $\lim_{z \rightarrow x} u_x(z) = 0$. (Just define: $u_x(z) := \frac{f(z) - f(x)}{z - x} - f'(x)$ for $z \neq x$)

Lemma 5.5: Linear approximation

$$f'(x) \text{ exists} \Leftrightarrow \exists L \in \mathbb{R} : \lim_{\delta \rightarrow 0^+} \sup_{|z - x| < \delta} \frac{1}{\delta} |f(z) - f(x) - L(z - x)| = 0.$$

Lemma 5.6: Sum & product rule

Let f, g be differentiable at x . Then so are $f + g$ and $f \cdot g$ and

$$\begin{aligned} (f + g)'(x) &= f'(x) + g'(x) \\ (f \cdot g)'(x) &= f'(x)g(x) + g'(x)f(x) \quad (\text{Leibniz rule}). \end{aligned}$$

Proof. For product rule, note that

$$f(z)g(z) - f(x)g(x) = (f(z) - f(x))g(z) + (g(z) - g(x))f(x).$$

Then

$$\frac{f(z)g(z) - f(x)g(x)}{z - x} = \frac{f(z) - f(x)}{z - x} g(z) + \frac{g(z) - g(x)}{z - x} f(x).$$

Since $g(z) \rightarrow g(x)$ by continuity of g , formula follows by sum & product rule for limit. \square

Lemma 5.7: Chain rule

Let f be differentiable at x and g at $f(x)$. Then $g \circ f$ is differentiable at x and

$$(g \circ f)'(x) = g'(f(x))f'(x) \quad \left(\frac{dg}{df} \frac{df}{dx} \right)$$

Proof. Define $v_{f(x)}$ such that $g(y) - g(f(x)) = (g'(f(x)) + v_{f(x)}(y))(y - f(x))$ and u_x such that $f(z) - f(x) = (f'(x) + u_x(z))(z - x)$.

$$\begin{aligned} (g \circ f)(z) - (g \circ f)(x) &= [g'(f(x)) + v_{f(x)}(f(z))](f(z) - f(x)) \\ &= [g'(f(x)) + v_{f(x)}(f(z))][f'(x) + u_x(z)](z - x) \end{aligned}$$

Dividing by $z - x \neq 0$, note that $f(z) \rightarrow f(x)$ implies $v_{f(x)}(f(z)) \rightarrow 0$ as $z \rightarrow x$, we are done. \square

Lemma 5.8

Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be injective on $\text{Dom}(f)$ and differentiable at $x \in \text{int}(\text{Dom}(f))$. Assume $f'(x) \neq 0$ and $f(x) \in \text{int}(\text{Ran}(f))$. Then f^{-1} is differentiable at $f(x)$ and

$$(f^{-1})'(f(x)) = \frac{1}{f'(x)}.$$

In Leibniz notation:

$$\frac{dy}{dx} = \frac{1}{\frac{dx}{dy}}.$$

Lemma 5.9: First derivative test

Let $f: [a, b] \rightarrow \mathbb{R}$ be continuous on $[a, b]$ and differentiable on (a, b) . Then if $x \in (a, b)$ is a local maximum of f (i.e. $\exists \delta > 0 \forall z \in \mathbb{R} : |z - x| < \delta \Rightarrow f(x) \geq f(z)$) then $f'(x) = 0$.

Proof.

$$z > x \wedge |z - x| < \delta \Rightarrow \frac{f(z) - f(x)}{z - x} \leq 0 \Rightarrow f'(x) \leq 0$$

and

$$z < x \wedge |z - x| < \delta \Rightarrow \frac{f(z) - f(x)}{z - x} \geq 0 \Rightarrow f'(x) \geq 0.$$

\square

6 4.6 Wednesday Week 2: Discussion

Recall: For, $x: [a, b] \rightarrow \mathbb{R}$, the total variation

$$V(f, [a, b]) = \sup_{\Pi} \sum_{i=1}^n |f(x_i) - f(x_{i-1})|$$

where $\Pi = \{a = x_0 < x_1 < \dots < x_n = b\}$. We say $f \in BV([a, b])$ if $V(f, [a, b]) < \infty$.

Theorem 6.1: Jordan decomposition

$$\forall f \in BV([a, b]) \exists h, g : [a, b] \rightarrow \mathbb{R} \text{ nondecreasing} : f = h - g.$$

Corollary 6.2

$f \in BV([a, b])$ can only have discontinuities of first kind and countably many of them.

Example 6.3. $f(x) = \sin x \in BV([-1, 1])$ since f is nondecreasing on $[-1, 1]$ and hence $V(f, [a, b]) = f(b) - f(a)$.

Example 6.4. $f(x) = \sin x \in BV([-M, M])$ by additive property of V .

Q. Does $BV([a, b])$ imply bounded on $[a, b]$?

Yes. By triangle inequality,

$$|f(x)| \leq |f(a)| + |f(a) - f(x)| \leq |f(a)| + V(f, [a, b]) < \infty.$$

Q. Does being bounded on $[a, b]$ imply $BV([a, b])$.

No. A counterexample is

$$f(x) = \begin{cases} \sin \frac{1}{x} & x \neq 0 \\ 0 & x = 0 \end{cases}$$

on $[0, 1]$.

Choose $x_n = 1/(n\pi/2)$ such that $\sin(1/x_n) = \sin(n\pi/2)$. Then $\sum_{i=1}^{2n} |f(x_i) - f(x_{i-1})| = \sum_{k=1}^n |f(x_{2k+1})| = n \rightarrow \infty$.

Example 6.5. Is

$$f(x) = \begin{cases} x \sin \frac{1}{x} & x \neq 0 \\ 0 & x = 0 \end{cases}$$

on $[0, 1]$ of bounded variation?

No. Choose the same x_n as above. Note that $f(x_n) = \frac{2}{n\pi} \sin(n\pi/2)$. Then $\sum_{i=1}^{2n} |f(x_i) - f(x_{i-1})| = \sum_{k=1}^n \frac{2}{(2k-1)\pi} \rightarrow \infty$.

Example 6.6. Is

$$f(x) = \begin{cases} x^2 \sin \frac{1}{x} & x \neq 0 \\ 0 & x = 0 \end{cases}$$

on $[0, 1]$ of bounded variation?

Yes. Note that

$$f'(0) = \lim_{t \rightarrow 0} \frac{t^2 \sin \frac{1}{t} - 0}{t} = \lim_{t \rightarrow 0} t \sin \frac{1}{t} = 0.$$

Note that for $x \neq 0$,

$$f'(x) = 2x \sin \frac{1}{x} + x^2 \left(-\frac{1}{x^2} \right) \cos \frac{1}{x} = 2x \sin \frac{1}{x} - \cos \frac{1}{x}$$

is bounded: $|f'(x)| \leq 2|x| + 1 \leq 3$.

Note that by mean value theorem, we have

$$\sum |f(x_i) - f(x_{i-1})| \leq \sum |f'(\xi)| (x_i - x_{i-1}) \leq M(b-a) < \infty$$

where $|f'(\xi)| \leq M$.

Then f is of bounded variation on $[0, 1]$.

Theorem 6.7

If f' exists and is bounded on $[a, b]$ then f is of bounded variation.

Q. Does the existence f' on $[a, b]$ and f being of bounded variation on $[a, b]$ imply f' is bounded on $[a, b]$?

7 4.7 Thursay Week 2: Mean-Value Theorems of Rolle, Lagrange and Cauchy. Applications: Monotone differentiable functions have derivative of one sign. Derivative of a differentiable function has no discontinuities of first kind (but those of second kind can occur densely). L'Hospital's Rule and its proof from Cauchy's MVT.

Mean value theorems

Last time: $f'(x)$ = derivative is linked to the local maxima and minima (first derivative test).

Theorem 7.1: Mean value theorem

Let $f: [a, b] \rightarrow \mathbb{R}$ be continuous on $[a, b]$ and differentiable on (a, b) . Then

1. (Rolle's theorem, 1691) $f(a) = f(b) \Rightarrow \exists x \in (a, b) : f'(x) = 0$,
2. (Lagrange's mean value theorem) $\exists x \in (a, b) : f'(x) = \frac{f(b)-f(a)}{b-a}$, and
3. (Cauchy mean value theorem, 1823) if also $g: [a, b] \rightarrow \mathbb{R}$ is continuous on $[a, b]$ and differentiable on (a, b) , then

$$\forall x \in (a, b) : g'(x) \neq 0 \Rightarrow g(a) \neq g(b) \wedge \exists x \in (a, b) : \frac{f'(x)}{g'(x)} = \frac{f(b) - f(a)}{g(b) - g(a)}.$$

Proof.

1. $f(a) = f(b) \wedge$ continuous function on $[a, b]$ achieves one of maximum and minimum on $(a, b) \Rightarrow \exists x \in (a, b) : x$ is local maximum or local minimum of f . Then $f'(x) = 0$.
2. Let $h(x) = f(x) - \frac{f(b)-f(a)}{b-a}(x-a)$. Then $h(a) = f(a)$, $h(b) = f(b) - \frac{f(b)-f(a)}{b-a}(b-a) = f(a)$. Then, by 1., $\exists x \in (a, b) : h'(x) = f'(x) - \frac{f(b)-f(a)}{b-a} = 0$.
3. Let $h(x) = f(x) - \frac{f(b)-f(a)}{g(b)-g(a)}(g(x) - g(a))$. Note that this is well defined since by 1. we have $g(b) \neq g(a)$. Then $h(a) = f(a) = h(b)$ so by 1. we have $\exists x \in (a, b) : h'(x) = f'(x) - \frac{f(b)-f(a)}{g(b)-g(a)}g'(x) = 0$.

□

Applications

Lemma 7.2

Let $f: [a, b] \rightarrow \mathbb{R}$ be continuous on $[a, b]$ and differentiable on (a, b) . Then

$$\forall x \in (a, b) : f'(x) \geq 0 \Leftrightarrow \forall x, y \in [a, b] : x \leq y \Rightarrow f(x) \leq f(y).$$

Proof. The \Leftarrow direction is immediate from the definition of limit $\left(\frac{f(y)-f(x)}{y-x} \geq 0\right)$.

For the \Rightarrow direction, if $\exists x \geq y : f(y) < f(x)$ then by the mean value theorem $\exists z \in (x, y) : f'(z) = \frac{f(y)-f(x)}{y-x} < 0$. □

8 4.8 Friday Week 2: Taylor's theorem via Mean Value Theorem (Rolle suffices). Riemann integral: motivation, definitions of marked partition, mesh of partition and Riemann sum. Notion of a function being Riemann integrable. Linearity of integral.

Taylor's theorem

Definition 8.1: Higher order derivatives

Define $f^{(0)} := f$ and for all $n \in \mathbb{N}$ define $f^{(n+1)}(x) := (f^{(n)})'(x)$ assuming the derivatives exist. We call $f^{(n)}$ the n -th derivative of f .

Theorem 8.2: Taylor's theorem (Taylor 1715, Gregory 1671)

Let $n \in \mathbb{N}$ and $f: (a, b) \rightarrow \mathbb{R}$ an $(n+1)$ -times differentiable function. Then

$$\forall x_0 \in (a, b) \forall x \in (x_0, b) \exists \xi \in (x_0, x) : f(x) = \underbrace{\sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} (x - x_0)^k}_{n\text{-th order Taylor polynomial at } x_0} + \frac{f^{(n+1)}(\xi)}{(n+1)!} (x - x_0)^{n+1}.$$

Proof. Based on MVT.

Denote

$$P_n(z) := \sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} (z - x_0)^k.$$

Pick $x \in (x_0, b)$ and denote

$$A := \frac{f(x) - P_n(x)}{(x - x_0)^{n+1}}.$$

Set

$$h(z) := f(z) - P_n(z) - A(z - x_0)^{n+1}.$$

Note that

$$\forall k \in \mathbb{N} : k \leq n \Rightarrow f^{(k)}(x_0) = 0.$$

We claim that

$$\forall k \in \mathbb{N} : 1 \leq k \leq n+1 \Rightarrow \exists \xi_k \in (x_0, x) : h^{(k)}(\xi_k) = 0.$$

For $k = 1$, the choice of A implies $h(x) = 0$ so since $h(x_0) = 0$, by Rolle's theorem

$$\exists \xi_1 \in (x_0, x) : h'(\xi_1) = 0.$$

Assume true for some $k \in \mathbb{N}$ such that $1 \leq k \leq n$. Then $h^{(k)}(x_0) = 0$ and $h^{(k)}(\xi_k) = 0$ for $\xi_k \in (x_0, x)$. Then by Rolle's theorem

$$\exists \xi_{k+1} \in (x_0, \xi_k) : h^{(k+1)}(\xi_{k+1}) = 0.$$

Now observe that $P_n^{(n+1)} = 0$. Then $0 = h^{(n+1)}(\xi_{n+1}) = f^{(n+1)}(\xi_{n+1}) - A(n+1)!$. Then

$$f(x) - P_n(x) = A(x - x_0)^{n+1} = \frac{f^{(n+1)}(\xi_{n+1})}{(n+1)!}(x - x_0)^{n+1}.$$

□

Riemann integral (Riemann 1854)

Goal: Given $f : [a, b] \rightarrow \mathbb{R}$, assign meaning to the area under the graph of f on $[a, b]$; namely to the set

$$\{(x, y) \in \mathbb{R}^2 : x \in [a, b] \wedge 0 \leq y \leq f(x)\} \quad (\text{for } f \geq 0).$$

Idea: Approximate f with a piecewise constant function and use that the area of a rectangle is “known.”

Definition 8.3

Given $[a, b]$, a **marked partition** Π of $[a, b]$ is two sequences $\{t_i\}_{i=0}^n, \{t_i^*\}_{i=1}^n$ such that

- $a = t_0 < t_1 < \dots < t_{n-1} < t_n = b$ and
- $\forall i = 1, \dots, n : t_i^* \in [t_{i-1}, t_i]$.

Definition 8.4

The **mesh** of Π is defined by $||\Pi|| := \max_{i=1, \dots, n} |t_i - t_{i-1}|$.

Definition 8.5

Given $f : [a, b] \rightarrow \mathbb{R}$ and a marked partition Π , the associated **Riemann sum** is

$$R(f, \Pi) := \sum_{i=1}^n f(t_i^*)(t_i - t_{i-1}).$$

Definition 8.6

A function $f: [a, b] \rightarrow \mathbb{R}$ is said to be **Riemann integrable** (on $[a, b]$) if there exists $L \in \mathbb{R}$ such that

$$\forall \varepsilon > 0 \exists \delta > 0 \forall \Pi = \text{marked partition of } [a, b] : \|\Pi\| < \delta \Rightarrow |R(f, \Pi) - L| < \varepsilon.$$

We sometimes write this as $\lim_{\|\Pi\| \rightarrow 0} R(f, \Pi) = L$ (this L is unique). Notation for L is $\int_a^b f(x) dx$.

Lemma 8.7: Additivity and homogeneity of Riemann integral

Let $f, g: [a, b] \rightarrow \mathbb{R}$ be Riemann integrable on $[a, b]$. Let $\alpha, \beta \in \mathbb{R}$. Then $\alpha f + \beta g$ is Riemann integrable on $[a, b]$ and

$$\int_a^b (\alpha f(x) + \beta g(x)) dx = \alpha \int_a^b f(x) dx + \beta \int_a^b g(x) dx.$$

Proof. Given $\varepsilon > 0$, pick $\delta > 0$ such that $\|\Pi\| < \delta$ implies

$$\left| R(f, \Pi) - \int_a^b f(x) dx \right| < \varepsilon \wedge \left| R(g, \Pi) - \int_a^b g(x) dx \right| < \varepsilon.$$

Since $R(\alpha f + \beta g, \Pi) = \alpha R(f, \Pi) + \beta R(g, \Pi)$,

$$\begin{aligned} & \left| R(\alpha f + \beta g, \Pi) - \alpha \int_a^b f(x) dx - \beta \int_a^b g(x) dx \right| \\ & \leq |\alpha| \left| R(f, \Pi) - \int_a^b f(x) dx \right| + |\beta| \left| R(g, \Pi) - \int_a^b g(x) dx \right| \\ & \leq (|\alpha| + |\beta|) \varepsilon. \end{aligned}$$

□

Corollary 8.8

Let $f, g: [0, \infty) \rightarrow \mathbb{R}$ be continuous on $[0, \infty)$ and differentiable on $(0, \infty)$. Then

$$f(0) \leq g(0) \wedge \forall x \in (0, \infty) : f'(x) \leq g'(x) \Rightarrow \forall x \in [0, \infty] : f(x) \leq g(x).$$

Example 8.9. $\forall x \geq 0 : e^x \geq 1 + x$.

Lemma 8.10

Let $f: [a, b] \rightarrow \mathbb{R}$ be continuous on $[a, b]$ and differentiable on (a, b) . Then f' has the intermediate value property.

Proof. Without loss of generality assume f' exists on $[\tilde{a}, \tilde{b}]$ such that $\tilde{a} < a < b < \tilde{b}$. Without loss of generality assume $f'(a) < f'(b)$. Let $t \in (f'(a), f'(b))$. Let $h(x) := f(x) - tx$. Then

$$h'(a) < 0 \Rightarrow \exists x \in (a, b) : h(x) < h(a).$$

With the same reasoning, we have

$$h'(b) > 0 \Rightarrow \exists y \in (a, b) : h(y) < h(b).$$

Then

$$\exists z \in (a, b) \text{ local minimum} \Rightarrow h'(z) = f'(z) - t = 0.$$

□

Corollary 8.11

The derivative of a differentiable function does not have discontinuities of first kind.

Example 8.12. Let

$$f(x) = \begin{cases} x^2 \sin(1/x) & x \neq 0 \\ 0 & x = 0. \end{cases}$$

Then $\forall x \neq 0 : f'(x) = x \sin(1/x) - \cos(1/x)$. $\lim_{x \rightarrow 0^\pm} f'(x)$ does not exist.

Also note that

$$\frac{f(x) - f(0)}{x - 0} = x \sin(1/x) \xrightarrow{x \rightarrow 0} 0$$

so $f'(0) = 0$.

Theorem 8.13: L'Hopital's rule, proved by Bernoulli 1694

Let $f, g : \mathbb{R} \rightarrow \mathbb{R}$ be continuous and differentiable on $(a - \delta, a + \delta)$ where $a \in \mathbb{R}$ and $\delta > 0$. Assume

$$f(a) = 0 = g(a) \wedge \forall x \in (a - \delta, a + \delta) \setminus \{a\} : g(x) \neq 0 \wedge g'(x) \neq 0.$$

Then

$$\lim_{x \rightarrow a} \frac{f'(x)}{g'(x)} \text{ exists} \Rightarrow \lim_{x \rightarrow a} \frac{f(x)}{g(x)} \text{ exists} \wedge \lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)}.$$

Proof. Let $x \in (a - \delta, a + \delta) \setminus \{a\}$. Then for $x > a$ we have

$$\frac{f(x)}{g(x)} \xrightarrow{f(a)=0, g(a)=0} \frac{f(x) - f(a)}{g(x) - g(a)} \xrightarrow[\text{Cauchy MVT}]{\exists z_x \in (a, x)} \frac{f'(z_x)}{g'(z_x)}.$$

Since $x \rightarrow a$ implies $z_x \rightarrow a$, existence of $\lim_{z \rightarrow a} \frac{f'(z)}{g'(z)}$ gives

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{z \rightarrow a} \frac{f'(z)}{g'(z)}.$$

□

Example 8.14. $\lim_{x \rightarrow 0} \frac{\sin x}{x} = \lim_{x \rightarrow 0} \frac{\cos x}{1} = 1$.

9 4.11 Monday Week 3

Last time: $f: [a, b] \rightarrow \mathbb{R}$ is Riemann integrable (RI) if

$$\exists L \in \mathbb{R} \forall \varepsilon > 0 \exists \delta > 0 \forall \Pi = \text{marked partition of } [a, b] : \|\Pi\| < \delta \Rightarrow |R(f, \Pi) - L| < \varepsilon.$$

Notation: $L = \int_a^b f(x) dx$.

We proved **linearity**:

$$\int_a^b (\alpha f(x) + \beta g(x)) dx = \alpha \int_a^b f(x) dx + \beta \int_a^b g(x) dx.$$

Lemma 9.1

If f is RI on $[a, b]$ then f is bounded on $[a, b]$.

Proof. RI $\Rightarrow \exists \delta > 0 \forall \Pi = \text{marked partition} : R(f, \Pi) \leq L + 1$. Then $\forall i = 1, \dots, n \forall \tilde{t}_i : f(\tilde{t}_i)(t_i - t_{i-1}) + \sum_{j=1, \dots, n, j \neq i} f(\tilde{t}_j^*)(t_j - t_{j-1}) \leq L + 1$, which means $\sup_{\tilde{t}_i \in [t_{i-1}, t_i]} f(\tilde{t}_i) < \infty$. Then $\sup_{x \in [a, b]} f(x) < \infty$. \square

Lemma 9.2: Additivity

Let $a < c < b$ be reals. If f is RI on $[a, c]$ and on $[c, b]$, then it is RI on $[a, b]$ and

$$\int_a^b f(x) dx = \int_a^c f(x) dx + \int_c^b f(x) dx.$$

Proof. Let $\varepsilon > 0$ and let $\delta > 0$ be such that $\forall \Pi = \text{marked partition of } [a, c]$ and $\forall \Pi' = \text{marked partition of } [c, b]$ such that $\|\Pi\| < \delta \wedge \|\Pi'\| < \delta$ we have

$$\left| R(f, \Pi) - \int_a^c f(x) dx \right| < \varepsilon \quad \wedge \quad \left| R(f, \Pi') - \int_c^b f(x) dx \right| < \varepsilon.$$

If $\tilde{\Pi}$ is a marked partition of $[a, b]$ with $\|\tilde{\Pi}\| < \delta$ containing c then

$$\left| R(f, \tilde{\Pi}) - \int_a^c f(x) dx - \int_c^b f(x) dx \right| < 2\varepsilon.$$

Suppose $\tilde{\Pi}$ does not contain c . Then adding c to $\tilde{\Pi}$ changes $R(f, \tilde{\Pi})$ by at most $2 \cdot 3\delta \sup_{x \in [a, b]} |f(x)|$. \square

Lemma 9.3

If f is RI on $[a, b]$ then

$$\left| \int_a^b f(x) dx \right| \leq (b - a) \underbrace{\sup_{x \in [a, b]} |f(x)|}_{< \infty}.$$

Proof. Note that

$$|R(f, \Pi)| = \left| \sum_{i=1}^n f(t_i^*)(t_i - t_{i-1}) \right| \leq \sum_{i=1}^n |f(t_i^*)(t_i - t_{i-1})| = R(|f|, \Pi) \leq \sup_{x \in [a, b]} |f(x)| \underbrace{\sum_{i=1}^n (t_i - t_{i-1})}_{=b-a}$$

□

Note. If we knew that $|f|$ is RI, then this gives

$$\left| \int_a^b f(x) dx \right| \leq \int_a^b |f(x)| dx.$$

Q: Sufficient conditions for RI?

A: We will answer this using Darboux's version of Riemann integral.

Definition 9.4

Let $f: [a, b] \rightarrow \mathbb{R}$ be bounded. Given an unmarked partition $\Pi = \{t_i\}_{i=1}^n$ of $[a, b]$, set

$$U(f, \Pi) := \sum_{i=1}^n \sup \{f(x) : x \in [t_{i-1}, t_i]\} (t_i - t_{i-1})$$

and

$$L(f, \Pi) := \sum_{i=1}^n \inf \{f(x) : x \in [t_{i-1}, t_i]\} (t_i - t_{i-1})$$

to be the **upper and lower Darboux sums**.

Note. $L(f, \Pi) \leq R(f, \Pi) \leq U(f, \Pi)$ for any marked partition Π .

Lemma 9.5

For all unmarked partitions Π and Π' of $[a, b]$ we have

$$L(f, \Pi) \leq U(f, \Pi').$$

Proof. Assume first Π is a subset of Π' , meaning that all points of Π are included in Π' . We claim that $U(f, \Pi') \leq U(f, \Pi)$ and $L(f, \Pi') \geq L(f, \Pi)$.

Note that if $\Pi' = \Pi \cup \{t\}$, let $[t_{i-1}, t_i]$ be the interval containing t . Then

$$\max \left\{ \sup_{x \in [t_{i-1}, t]} f(x), \sup_{x \in [t, t_i]} f(x) \right\} \sup_{x \in [t_{i-1}, t_i]} f(x),$$

resulting in $U(f, \Pi') \leq U(f, \Pi)$.

Now let Π and Π' be arbitrary and $\Pi \cup \Pi'$ be their common refinement. Then

$$L(f, \Pi) \leq L(f, \Pi \cup \Pi') \leq U(f, \Pi \cup \Pi') \leq U(f, \Pi').$$

□

Definition 9.6

Set

$$\int_a^b f(x) dx := \sup \{L(f, \Pi) : \Pi = \text{partition of } [a, b]\}$$

and

$$\overline{\int_a^b f(x) dx} := \inf \{U(f, \Pi) : \Pi = \text{partition of } [a, b]\}$$

to be the **lower and upper Darboux integrals**.

Note.

$$\int_a^b f(x) dx \leq \overline{\int_a^b f(x) dx}.$$

Definition 9.7

We say that a bounded f is **Darboux integrable on $[a, b]$** if

$$\int_a^b f(x) dx = \overline{\int_a^b f(x) dx}.$$

10 4.13 Wednesday Week 3

Riemann integral continued

Last time: $U(f, \Pi)$ and $L(f, \Pi)$ are the upper and lower Darboux sums. Note that

$$\forall \Pi, \Pi' : L(f, \Pi) \leq U(f, \Pi').$$

Then

$$\overline{\int_a^b f(x) dx} = \inf \{U(f, \Pi) : \Pi \text{ partition}\}$$

and

$$\int_a^b f(x) dx = \sup \{L(f, \Pi) : \Pi \text{ partition}\}$$

obey

$$\int_a^b f(x) dx \leq \overline{\int_a^b f(x) dx}.$$

Definition 10.1

$f: [a, b] \rightarrow \mathbb{R}$ bounded is **Darboux integrable** if

$$\int_a^b f(x) dx = \overline{\int_a^b f(x) dx}.$$

Lemma 10.2

For every $f: [a, b] \rightarrow \mathbb{R}$:

$$f \text{ Darboux integrable} \Leftrightarrow \forall \varepsilon > 0 \exists \Pi \text{ partition : } U(f, \Pi) - L(f, \Pi) < \varepsilon.$$

Proof. By definition,

$$\forall \varepsilon > 0 \exists \Pi, \tilde{\Pi} : U(f, \Pi) < \overline{\int_a^b f(x) dx} + \varepsilon \quad \wedge \quad L(f, \tilde{\Pi}) > \underline{\int_a^b f(x) dx} - \varepsilon.$$

Then

$$U(f, \Pi \cup \tilde{\Pi}) - L(f, \Pi \cup \tilde{\Pi}) \leq U(f, \Pi) - L(f, \tilde{\Pi}) \leq \overline{\int_a^b f(x) dx} - \underline{\int_a^b f(x) dx} + 2\varepsilon.$$

Then the equality of the Darboux integrals implies the left to right direction of the lemma.

For the converse,

$$0 \leq \overline{\int_a^b f(x) dx} - \underline{\int_a^b f(x) dx} \leq U(f, \Pi) - L(f, \Pi) < \varepsilon.$$

□

Lemma 10.3

Let Π and Π' be unmarked partitions. Then

$$U(f, \Pi') \geq U(f, \Pi) - 2 |\Pi'| \|\Pi\| \|f\|$$

and

$$L(f, \Pi') \leq L(f, \Pi) + 2 |\Pi'| \|\Pi\| \|f\|.$$

where $\|f\| := \sup_{x \in [a, b]} |f(x)|$.

Proof. Note that

$$U(f, \Pi') \geq U(f, \Pi \cup \Pi')$$

and for $f \geq 0$, dropping intervals of Π that receive points in Π' from $U(f, \Pi)$ changes the result by at most $2 |\Pi'| \|\Pi\| \|f\|$. □

Theorem 10.4

For every $f: [a, b] \rightarrow \mathbb{R}$ bounded:

$$f \text{ Riemann integrable} \Leftrightarrow f \text{ Darboux integrable.}$$

If both are true then

$$\int_a^b f(x) dx = \int_a^b f(x) dx = \overline{\int_a^b f(x) dx}.$$

Proof. \Rightarrow : RI means that

$$\exists L \in \mathbb{R} \exists \delta > 0 \forall \Pi \text{ partition with } \|\Pi\| < \delta : |R(f, \Pi) - L| < \varepsilon.$$

Pick $N \in \mathbb{N}$ such that $N > (b - a)/\delta$, define $\Pi = \{t_i\}_{i=1}^n$ such that $t_i - t_{i-1} = \frac{b-a}{N} < \delta$. Now pick $t_i^* \in [t_{i-1}, t_i]$ such that

$$f(t_i^*) \geq \sup \{f(x) : x \in [t_{i-1}, t_i]\} - \frac{\varepsilon}{b-a}$$

and $\tilde{t}_i^* \in [t_{i-1}, t_i]$ such that

$$f(\tilde{t}_i^*) \leq \inf \{f(x) : x \in [t_{i-1}, t_i]\} + \frac{\varepsilon}{b-a}.$$

Then let Π be the partition with marked points $\{t_i^*\}_{i=1}^N$ and $\tilde{\Pi}$ be the partition with marked points $\{\tilde{t}_i^*\}_{i=1}^N$.

Then

$$U(f, \Pi) \leq \sum_{i=1}^N \left(f(t_i^*) + \frac{\varepsilon}{b-a} \right) (t_i - t_{i-1}) = R(f, \Pi) + \varepsilon$$

and

$$L(f, \tilde{\Pi}) \geq \sum_{i=1}^n \left(f(\tilde{t}_i^*) - \frac{\varepsilon}{b-a} \right) (t_i - t_{i-1}) = R(f, \tilde{\Pi}) - \varepsilon.$$

Now

$$\begin{aligned} U(f, \Pi \cup \tilde{\Pi}) - L(f, \Pi \cup \tilde{\Pi}) &\leq U(f, \Pi) - L(f, \tilde{\Pi}) \\ &\leq R(f, \Pi) - R(f, \tilde{\Pi}) + 2\varepsilon \\ &\leq |R(f, \Pi) - L| + |R(f, \tilde{\Pi}) - L| + 2\varepsilon \\ &\leq 4\varepsilon. \end{aligned}$$

\Leftarrow : $\forall \varepsilon > 0 \exists \Pi'$ partition such that $U(f, \Pi') - L(f, \Pi') < \varepsilon$. Pick any Π and $\tilde{\Pi}$ marked partitions with $\|\tilde{\Pi}\|, \|\Pi\| < \delta := \varepsilon / (\|\Pi'\| \|f\|)$ ($f \neq 0$).

Then

$$R(f, \Pi) \leq U(f, \Pi) \stackrel{\text{by Lemma 10.3}}{\leq} U(f, \Pi') + \underbrace{2 \|\Pi'\| \|\Pi\| \|f\|}_{\leq \varepsilon}$$

and

$$R(f, \tilde{\Pi}) \geq L(f, \tilde{\Pi}) \stackrel{\text{by Lemma 10.3}}{\geq} L(f, \Pi') - \underbrace{2 \|\Pi'\| \|\tilde{\Pi}\| \|f\|}_{\leq \varepsilon}.$$

Then

$$|R(f, \tilde{\Pi}) - R(f, \Pi)| \leq U(f, \Pi') - L(f, \Pi') + 4\varepsilon \leq 5\varepsilon.$$

Let $\{\Pi_n\}$ be an arbitrary sequence of marked partitions such that

$$\|\Pi_n\| \rightarrow 0 \quad \wedge \quad L := \lim_{n \rightarrow \infty} R(f, \Pi_n) \text{ exists.}$$

This exists by Bolzano-Weierstrass theorem.

Then

$$|R(f, \Pi) - L| \leq |R(f, \Pi_n) - L| + |R(f, \Pi) - R(f, \Pi_n)| \underset{\text{once } \|\Pi_n\| < \delta}{\leq} |R(f, \Pi_n) - L| + 5\varepsilon \xrightarrow{n \rightarrow \infty} 5\varepsilon.$$

Then we showed that

$$\exists L \in \mathbb{R} \forall \varepsilon > 0 \exists \delta > 0 \forall \Pi \text{ marked partition : } \|\Pi\| < \delta \Rightarrow |R(f, \Pi) - L| \leq 5\varepsilon.$$

□

Corollary 10.5

Let $f: [a, b] \rightarrow \mathbb{R}$ be bounded. Then

$$f \text{ is RI} \Leftrightarrow \forall \varepsilon > 0 \exists \Pi = \{t_i\}_{i=1}^n \text{ unmarked partition : } \sum_{i=1}^N \text{osc}(f, [t_{i-1}, t_i])(t_i - t_{i-1}) < \varepsilon$$

where $\text{osc}(f, A) = \sup_{x \in A} f(x) - \inf_{x \in A} f(x)$

Example 10.6. The dirichlet function

$$f(x) = \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}$$

is not RI.

Example 10.7. The function

$$f(x) = \begin{cases} \frac{1}{n+1} & x = q_n \\ 0 & x \notin \mathbb{Q} \end{cases}$$

is RI.

11 4.15 Friday Week 3

Riemann Integrability - criteria and characterization

Last time: $\forall f: [a, b] \rightarrow \mathbb{R}$ bounded,

$$f \text{ RI} \Leftrightarrow \forall \varepsilon > 0 \exists \Pi = \{t_i\}_{i=1}^n \text{ partition of } [a, b] : \sum_{i=1}^n \text{osc}(f, [t_{i-1}, t_i]) |t_i - t_{i-1}| < \varepsilon$$

where

$$\begin{aligned} \text{osc}(f, A) &:= \sup \{|f(y) - f(x)| : x, y \in A\} \\ &= \sup_{x \in A} f(x) - \inf_{x \in A} f(x) (A \neq \emptyset). \end{aligned}$$

Lemma 11.1

Let $f, g: [a, b] \rightarrow \mathbb{R}$. Then

1. f RI $\Rightarrow |f|$ RI and
2. f, g RI $\Rightarrow f \cdot g$ RI.

Proof. Note that

$$||f|(x) - |f|(y)| = ||f(x)| - |f(y)|| \leq |f(x) - f(y)|.$$

Then

$$\text{osc}(f, A) \leq \text{osc}(|f|, A).$$

Then

$$f \text{ RI} \Rightarrow |f| \text{ RI}.$$

Note that a counterexample for the converse is Dirichlet's function. □

Theorem 11.2

For all $f: [a, b] \rightarrow \mathbb{R}$ we have

$$f \text{ continuous} \Rightarrow f \text{ RI}.$$

Proof. Note that $[a, b]$ compact and f continuous implies that f is uniformly continuous. Then for all $\varepsilon > 0$ there exists $\delta > 0$ such that for all $s, t \in [a, b]$ we have

$$0 < |s - t| < \delta \Rightarrow \text{osc}(f, [s, t]) < \frac{\varepsilon}{b - a}.$$

Then for all

$$\forall \Pi : ||\Pi|| < \delta \Rightarrow \sum_{i=1}^n \text{osc}(f, [t_{i-1}, t_i])(t_i - t_{i-1}) \leq \sum_{i=1}^n \frac{\varepsilon}{b - a} (t_i - t_{i-1}) \leq \varepsilon.$$

□

Lemma 11.3

Let $f: [a, b] \rightarrow \mathbb{R}$ be bounded and such that f has only finitely many discontinuities. Then f is RI.

Proof. Let x_1, \dots, x_m enumerate discontinuity points of f . Pick $\varepsilon > 0$. Suppose without loss of generality $||f|| \neq 0$. Let $\delta < \frac{\varepsilon}{m||f||}$. Then

$$\text{osc}(f, [x_i - \delta, x_i + \delta] \cap [a, b]) \leq 2||f||.$$

Next, note that $[a, b] \setminus \bigcup_{i=1}^m (x_i - \delta, x_i + \delta)$ is closed and thus compact. Then f is uniformly continuous on this set. Then there exists $\delta' > 0$ such that for all $[s, t] \subseteq$ this set we have

$$0 < |s - t| \leq \delta' \Rightarrow \text{osc}(f, [s, t]) \leq \frac{\varepsilon}{b - a}.$$

Now partition $[a, b] \setminus \bigcup_{i=1}^m (x_i - \delta, x_i + \delta)$ into intervals of length $\leq \delta'$. Combine them with intervals $[x_i - \delta, x_i + \delta]$. Now take $\Pi =$ set of endpoints of these intervals. Then

$$\sum_{i=1}^n \text{osc}(f, [t_{i-1}, t_i])(t_i - t_{i-1}) \leq m \cdot 2||f|| \cdot 2\delta + \frac{\varepsilon}{b - a} (b - a) \leq 5\varepsilon.$$

□

Lemma 11.4

Let $f : [a, b] \rightarrow \mathbb{R}$ be bounded.

f has no discontinuities of second kind $\Rightarrow f$ RI.

Proof. Key idea:

$$\forall \eta > 0 : \left\{ x \in (a, b) : \text{diam} \left\{ \lim_{z \rightarrow x^+} f(z), \lim_{z \rightarrow x^-} f(z), f(x) \right\} > \eta \right\} \text{ is finite.}$$

□

Example 11.5.

$$f(x) = \begin{cases} \frac{1}{n+1} & x = q_n \\ 0 & x \notin \mathbb{Q}. \end{cases}$$

It gets worse: Let

$$C := \left\{ \sum_{i \in \mathbb{N}} \frac{2\sigma_i}{3^{i+1}} : \{\sigma_i\}_{i \in \mathbb{N}} \in \{0, 1\}^{\mathbb{N}} \right\}$$

be Cantor's ternary set.

Then $C = \bigcap_{n \in \mathbb{N}} C_n$ where

$$C_n = \left\{ \sum_{i=1}^n \frac{\sigma_i}{3^{i+1}} + [0, 3^{-n-1}] : \sigma_1, \dots, \sigma_n \in \{0, 1\} \right\}.$$

Lemma 11.6

The function

$$1_C(x) = \begin{cases} 1 & x \in C \\ 0 & x \notin C \end{cases}$$

is RI.

Proof. Let I_1, \dots, I_{2^n} be intervals constituting C_n . Define

$$J_k = \left\{ x \in [0, 1] : \text{dist}(x, I_k) < \frac{1}{3^{n+1}} \right\}.$$

Then

$$\text{length}(J_k) = \text{length}(I_k) + 2 \cdot \frac{1}{3^{n+1}} \leq \frac{1}{3^n}.$$

Take Π to be the endpoints of $\{J_k\}_{k=1}^{2^n}$. Then

$$\sum_{i=1}^m \text{osc}(f, [t_{i-1}, t_i]) |t_i - t_{i-1}| \leq \sum_{k=1}^{2^n} \text{length}(J_k) \leq 2^n \cdot \frac{1}{3^n} \xrightarrow{n \rightarrow \infty} 0.$$

□

12 4.18 Monday Week 4

Characterizing Riemann integrability

Sufficient conditions for RI: continuity, finite number of discontinuities, no discontinuities of second kind.

Necessary condition for RI: boundedness.

Definition 12.1

A set $A \subseteq \mathbb{R}$ is of **zero length** if

$$\forall \varepsilon > 0 \exists \{(a_i, b_i)\}_{i \in \mathbb{N}} \text{ intervals} : A \subseteq \bigcup_{i \in \mathbb{N}} (a_i, b_i) \quad \wedge \quad \sum_{i \in \mathbb{N}} (b_i - a_i) < \varepsilon.$$

Lemma 12.2

In the definition of zero length, closed intervals can be used.

Proof. If $A \subseteq \bigcup_{i \in \mathbb{N}} [a_i, b_i]$, let $\tilde{a}_i = a_i - \varepsilon/2^i$ and $\tilde{b}_i = b_i + \varepsilon/2^i$. Then

$$A \subseteq \bigcup_{i \in \mathbb{N}} (\tilde{a}_i, \tilde{b}_i)$$

and

$$\sum_{i \in \mathbb{N}} (\tilde{b}_i - \tilde{a}_i) = \sum_{i \in \mathbb{N}} (b_i - a_i) + \sum_{i \in \mathbb{N}} 2 \cdot \frac{\varepsilon}{2^i} = \sum_{i \in \mathbb{N}} (b_i - a_i) + 4\varepsilon.$$

□

Lemma 12.3

Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be bounded. Set

$$M_f(x) = \inf_{\delta > 0} \sup_{z: |z-x| < \delta} f(z)$$

and

$$m_f(x) = \sup_{\delta > 0} \inf_{z: |z-x| < \delta} f(z).$$

Then

1. $\forall x \in \mathbb{R} : f \text{ continuous at } x \Leftrightarrow M_f(x) = m_f(x),$
2. $\forall x \in \mathbb{R} \forall \delta : \max \{ \text{osc}(f, [x - \delta, x]), \text{osc}(f, [x - \delta, x]) \} \geq M_f(x) - m_f(x),$ and
3. $\forall x \in \mathbb{R} : \lim_{\delta \rightarrow 0} \text{osc}(f, [x - \delta, x + \delta]) = M_f(x) - m_f(x).$

Theorem 12.4: Lebesgue's characterization of Riemann integrability

Let $f: [a, b] \rightarrow \mathbb{R}$ be bounded. Then

$$f \text{ RI} \Leftrightarrow \{x \in [a, b] : f \text{ discontinuous at } x\} \text{ is zero length.}$$

Proof. \Rightarrow : Let $f : [a, b] \rightarrow \mathbb{R}$ be bounded and RI.

Pick $\varepsilon > 0$. Then RI implies

$$\forall n \in \mathbb{N} \exists \Pi = \{t_i^n\}_{i=1}^{m(n)} \text{ partition of } [a, b] : \sum_{i=1}^{m(n)} \text{osc}(f, [t_{i-1}^n, t_i^n])(t_i^n - t_{i-1}^n) < \varepsilon 4^{-n}.$$

Set $I_n := \{i = 1, \dots, m(n) : \text{osc}(f, [t_{i-1}^n, t_i^n]) > 2^{-n}\}$. Then

$$\sum_{i \in I_n} (t_i^n - t_{i-1}^n) \stackrel{\text{Markov's inequality}}{\leq} \sum_{i \in I_n} \frac{\text{osc}(f, [t_{i-1}^n, t_i^n])}{2^{-n}} (t_i^n - t_{i-1}^n) \leq 2^n \sum_{i=1}^{m(n)} \text{osc}(f, [t_{i-1}^n, t_i^n])(t_i^n - t_{i-1}^n) \leq 2^n \cdot \varepsilon 4^{-n} = \varepsilon 2^{-n}.$$

Now

$$\{x \in [a, b] : M_f(x) \neq m_f(x)\} \subseteq \bigcup_{n \geq 1} \bigcup_{i \in I_n} [t_{i-1}^n, t_i^n].$$

Then

$$\sum_{n \geq 1} \sum_{i \in I_n} (t_i^n - t_{i-1}^n) \leq \sum_{n \geq 1} \varepsilon 2^{-n} = \varepsilon.$$

Then f RI $\Rightarrow \{x \in [a, b] : M_f(x) \neq m_f(x)\}$ is zero length.

\Leftarrow : Let $\varepsilon > 0$ and let $\{J_i\}_{i \in \mathbb{N}}$ be open intervals such that

$$\{x \in [a, b] : M_f(x) \neq m_f(x)\} \subseteq \bigcup_{i \in \mathbb{N}} J_i \quad \wedge \quad \sum_{i \in \mathbb{N}} \text{length}(J_i) < \frac{\varepsilon}{2\varepsilon \|f\|} (f \neq 0).$$

Since $M_f(x) = m_f(x) \Rightarrow x$ is continuous:

$$\forall x \in [a, b] : M_f(x) = m_f(x) \Rightarrow \exists \delta_x > 0 : \text{osc}(f, (x - \delta_x, x + \delta_x)) < \frac{\varepsilon}{b - a}.$$

Then intervals $\{J_i\}_{i \in \mathbb{N}} \cup \{(x - \delta, x + \delta) : M_f(x) = m_f(x)\}$ cover $[a, b]$. Then by Heine-Borel theorem,

$$\exists m, n \in \mathbb{N} \exists x_0, \dots, x_m \in \{x \in [a, b] : M_f(x) = m_f(x)\} : [a, b] \subseteq \bigcup_{i=0}^m J_i \cup \bigcup_{j=0}^m (x_j - \delta_{x_j}, x_j + \delta_{x_j}).$$

Let $\Pi = \{t_i\}_{i=1}^N$ be a partition containing of all endpoints of the intervals $(x_j - \delta_{x_j}, x_j + \delta_{x_j})$. Let $k = \{i = 1, \dots, N : [t_{i-1}, t_i] \subseteq \bigcup_{j=1}^m (x_j - \delta_{x_j}, x_j + \delta_{x_j})\}$. Then

$$\forall i \in K : \text{osc}(f, [t_{i-1}, t_i]) < \frac{\varepsilon}{b - a}$$

and

$$\sum_{i \notin K} \text{osc}(f, [t_{i-1}, t_i]) \leq 2\|f\| \cdot \sum_{i \notin K} (t_i - t_{i-1}) < 2\|f\| \sum_{i \in \mathbb{N}} \text{length}(J_i) < \varepsilon.$$

Then

$$\sum_{i=1}^n \text{osc}(f, [t_{i-1}, t_i])(t_i - t_{i-1}) \leq \sum_{i \in K} \text{osc}(f, [t_{i-1}, t_i])(t_i - t_{i-1}) + \sum_{i \notin K} \text{osc}(f, [t_{i-1}, t_i])(t_i - t_{i-1}) \leq \frac{\varepsilon}{b - a} (b - a) + \varepsilon = 2\varepsilon.$$

□

13 4.20 Wednesday Week 4

Derivative vs. integral, FTC, ...

Last time: f RI $\Leftrightarrow \{x \in [a, b] : f \text{ discontinuous at } x\}$ is of zero length.

Corollary 13.1

$$f \text{ RI} \wedge \{x \in [a, b] : g(x) \neq f(x)\} \text{ is of zero length} \Rightarrow g \text{ RI} \wedge \int_a^b g(x) dx = \int_a^b f(x) dx.$$

Today: Newton / Leibniz FTC:

$$\frac{d}{dx} \int_a^x f(t) dt = f(x) \quad \wedge \quad \int_a^b \frac{d}{dx} f(t) dt = f(b) - f(a).$$

Note. These are not true without conditions.

Lemma 13.2

Let $a < b$ be reals and $f : [a, b] \rightarrow \mathbb{R}$ be an RI function on $[a, b]$. Set $F(x) = \int_a^x f(t) dt$. Then F is Lipschitz continuous.

Proof. If $a \leq x < y \leq b$ then additivity implies

$$F(y) - F(x) = \int_0^y f(t) dt - \int_0^x f(t) dt = \int_x^y f(t) dt.$$

Note that f RI $\Rightarrow f$ bounded. Then

$$|F(y) - F(x)| = \left| \int_x^y f(t) dt \right| \leq \|f\| \cdot |y - x|.$$

□

Example 13.3.

$$|x| = \int_0^x t(1_{[0, \infty)} - 1_{(-\infty, 0)}) dt.$$

Q: Is every Lipschitz function a Riemann integral?

Lemma 13.4

Let f be RI on $[a, b]$. Set $F(x) = \int_a^b f(t) dt$. Then

$$\forall x \in (a, b) : f \text{ continuous at } x \Rightarrow F'(x) \text{ exists} \wedge F'(x) = f(x).$$

Proof. Let $y \in (x, b)$. Then

$$F(y) - F(x) - f(x)(y - x) = \int_x^y (f(t) - f(x)) dt.$$

Then

$$\left| \frac{F(y) - F(x)}{y - x} - f(x) \right| \leq \sup_{t \in [x, y]} |f(y) - f(x)| \xrightarrow{y \rightarrow x^+} 0 \text{ by right continuity of } f.$$

Then $F'^+(x) = f(x)$. Similarly, $F'^-(x) = f(x)$. □

Example 13.5.

$$f(x) = 1_{1/(n+1), n \in \mathbb{N}}.$$

Note that $F(x) = 0$ for all $x \in \mathbb{R}$.

Corollary 13.6: Fundamental theorem of calculus I

Let $f: [a, b] \rightarrow \mathbb{R}$ be continuous. Then

$$\forall x \in (a, b) : \frac{d}{dx} \int_a^x f(t) dt = f(x).$$

Note.

- The integral is an antiderivative / primitive function. Notation $\int f(t) dt$;
- $\frac{d}{dt} \int_x^b f(t) dt = -f(x)$;
- $\frac{d}{dx} \int_{g(x)}^{h(x)} f(t) dt = f(h(x))h'(x) - f(g(x))g'(x)$.

Theorem 13.7

Let $f: [a, b] \rightarrow \mathbb{R}$ be continuous on $[a, b]$ and differentiable on (a, b) . (Choose $f'(a), f'(b)$) arbitrarily. Then

$$f \text{ RI} \Rightarrow \int_a^b f'(t) dt = f(b) - f(a).$$

Proof. Let $\varepsilon > 0$. Then f' RI implies

$$\exists \delta > 0 \forall \Pi : \|\Pi\| < \varepsilon \Rightarrow \left| R(f', \Pi) - \int_a^b f'(t) dt \right| < \varepsilon.$$

Pick $n \in \mathbb{N}$ such that $n\delta > (b - a)$. Set $t_i := a + \frac{i}{n}(b - a)$ where $i = 0, \dots, n$.

Then, by the mean value theorem, for all $i = 1, \dots, n$ we have

$$\exists t_i^* \in (t_{i-1}, t_i) : f(t_i) - f(t_{i-1}) = f'(t_i^*)(t_i - t_{i-1}).$$

Let $\Pi := (\{t_i\}, \{t_i^*\})$. Then

$$f(b) - f(a) = \sum_{i=1}^n (f(t_i) - f(t_{i-1})) = \sum_{i=1}^n f'(t_i^*)(t_i - t_{i-1}) = R(f', \Pi).$$

Then

$$\left| f(b) - f(a) - \int_a^b f'(t) dt \right| < \varepsilon.$$

□

Volterra's example

$\exists F: [0, 1] \rightarrow \mathbb{R}$ continuous : $F'(x)$ exists for all $x \in [0, 1] \wedge F'$ bounded $\wedge F'$ is not RI.

This is a major deficiency in Riemann's theory that led Lebesgue to the formulation of the Lebesgue integral.

Corollary 13.8: Integration by parts

Let $f, g: [a, b] \rightarrow \mathbb{R}$ be continuous on $[a, b]$ and differentiable on (a, b) . Then

$$f'g \text{ RI} \wedge fg' \text{ RI} \Rightarrow \int_a^b f'(x)g(x) dx = f(b)g(b) - f(a)g(a) - \int_a^b f(x)g'(x) dx.$$

Proof. Note that

$$f'g \text{ RI} \wedge g'f \text{ RI} \Rightarrow (fg)' \text{ RI}.$$

Then

$$f(b)g(b) - f(a)g(a) = \int_a^b (fg)'(x) dx = \int_a^b f'(x)g(x) dx + \int_a^b f(x)g'(x) dx.$$

□

Corollary 13.9

Let $f: [c, d] \rightarrow \mathbb{R}$ and $\varphi: [a, b] \rightarrow \mathbb{R}$ be functions. Assume

1. φ is continuous on $[a, b]$ and differentiable on (a, b) ,
2. f is continuous on $[c, d]$, and
3. $(f \circ \varphi)\varphi'$ is RI on $[a, b]$.

Then

$$\int_{\varphi(a)}^{\varphi(b)} f(x) dx = \int_a^b (f \circ \varphi)(t)\varphi'(t) dt.$$

Proof. Note that

$$F(x) = \int_a^x f(t) dt \xrightarrow{\text{FTC I}} F'(x) = f(x).$$

Then

$$\int_{\varphi(a)}^{\varphi(b)} f(t) dt \xrightarrow{\text{FTC II}} F(\varphi(b)) - F(\varphi(a)) \xrightarrow{\text{FTC II}} \int_a^b \frac{d}{dx}(F \circ \varphi)(x) dx = \int_a^b (f \circ \varphi)(x)\varphi'(x) dx.$$

□

14 4.25 Monday Week 5

Taylor's theorem

Last time: FTC I:

$$f \text{ continuous} \Rightarrow F(x) = \int_a^x f(t) dt \text{ differentiable} \wedge F'(x) = f(x).$$

FTC II:

$$F \text{ continuous on } [a, b] \wedge F' \text{ exists on } (a, b) \wedge F' \text{ RI} \Rightarrow F(b) - F(a) = \int_a^b F'(x) dx.$$

Cantor's function ("Devil's staircase"):

$$x \in \sum_{i=0}^n \frac{2\sigma_i}{3^{in}} + [0, 3^{-n-1}] \mapsto F(x) = \sum_{i=0}^n \frac{\sigma_i}{2^{i+1}}.$$

This is simply not an integral of a derivative (not Lipschitz but Holder continuous with a coefficient less than 1). F' exists at every point excluding the Cantor set, which is 0.

Consequences of the FTC:

- Substitution rule
- Integration by parts

Theorem 14.1: Taylor's theorem with remainder

Let $f: (a, b) \rightarrow \mathbb{R}$ be $(n+1)$ -times differentiable with $f^{(n+1)}$ Riemann integrable. Then

$$\forall x, x_0 \in (a, b): f(x) = \sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} (x - x_0)^k + \frac{1}{n!} \int_{x_0}^x f^{(n+1)}(z) (x - z)^n dz.$$

Proof. $n = 0$: FTC: f' exists and f' is RI by assumption.

$$f(x) = f(x_0) + \int_{x_0}^x f'(z) dz.$$

$n \Rightarrow n+1$: Assume $f^{(n+2)}$ exists and is RI. Then $f^{(n+1)}$ is continuous and therefore RI. Then

$$\begin{aligned} \frac{1}{n!} \int f^{(n+1)}(z) (x - z)^n dz &= \frac{1}{n!} \int f^{(n+1)}(z) \frac{d}{dz} \left(-\frac{(x - z)^{n+1}}{n+1} \right) dz \\ &\stackrel{IBP}{=} \frac{1}{n!} f^{(n+1)}(z) \left(-\frac{(x - z)^{n+1}}{n+1} \right) \Big|_{x_0}^x - \int_{x_0}^x f^{(n+2)}(z) \left(-\frac{(x - z)^{n+1}}{n+1} \right) dz \\ &= \frac{f^{(n+1)}(x_0)}{(n+1)!} (x - x_0)^n + \int_{x_0}^x \frac{f^{(n+2)}(z)}{(n+1)!} (x - z)^{n+1} dz. \end{aligned}$$

Then

$$f(x) - P_n(x) \stackrel{(n)}{=} \text{LHS} = P_{n+1}(x) - P_n(x) + \int_{x_0}^x \frac{f^{(n+2)}(z)}{n+1} (x - z)^{n+1} dz.$$

□

Stieljes integral

Idea: Measure length of intervals using other functions than just $g(x) = x$.

Definition 14.2

Let $\Pi = (\{t_i\}_{i=0}^n, \{t_i^*\}_{i=1}^n)$ be a marked partition of $[a, b]$. For $f, g: [a, b] \rightarrow \mathbb{R}$,

$$S(f, dg, \Pi) := \sum_{i=1}^n f(t_i^*)[g(t_i) - g(t_{i-1})]$$

is the **Riemann-Stieljes sum** of f with respect to g .

Definition 14.3

Let $f, g: [a, b] \rightarrow \mathbb{R}$. We say that “ f is Stieljes integrable with respect to g on $[a, b]$ ” if

$$\exists L \in \mathbb{R} \forall \varepsilon > 0 \exists \delta > 0 \forall \Pi \text{ marked partition of } [a, b] : \|\Pi\| < \delta \Rightarrow |S(f, dg, \Pi) - L| < \varepsilon$$

or in short,

$$\lim_{\|\Pi\| \rightarrow 0} S(f, dg, \Pi) \text{ exists.}$$

Note.

- Such an L is unique (if it exists) and so we denote it $\int_a^b f(x) dg(x) = \int_a^b f dg$.
- For $g(x) = x$, we get the Riemann integral.
- If “length” of $[t, s]$ is given by $g(s) - g(t)$, then $\int f dg$ corresponds to “area” with lengths in \mathbb{R} measured using g .
- In probability: g = cumulative distribution function of a random variable x ($g(t) := P(x \leq t)$) then

$$\int f(x) dg(x) = E(f(X)) = \text{expectation of } f(X).$$

- In economics: $f(t)$ = price of stock at time t , $g(t)$ = current holding of the stock then

$$\int_a^b f dg = \text{total money earned in time interval } [a, b].$$

This shows g may not be monotone.

15 4.27 Wednesday Week 5

Stieljes integral

Last time:

$$S(f, dg, \Pi) = \sum_{i=1}^n f(t_i^*)(g(t_i) - g(t_{i-1}))$$

$$\int_a^b f dg := \lim_{\|\Pi\| \rightarrow 0} S(f, dg, \Pi) \text{ wherever it exists.}$$

We call this the Stieljes integral in the Riemann sense.

Notation: $RS(g, [a, b]) := \{f : [a, b] \rightarrow \mathbb{R} : \int_a^b f dg \text{ exists}\}$

Lemma 15.1: Linearity

Let $h : [a, b] \rightarrow \mathbb{R}$ be given. Then

$$\forall f, g \in RS(h, [a, b]) \forall \alpha, \beta \in \mathbb{R} : \alpha f + \beta g \in RS(h, [a, b]) \wedge \int_a^b (\alpha f + \beta g) dh = \alpha \int_a^b f dh + \beta \int_a^b g dh.$$

Lemma 15.2: Additivity

Let $g : [a, b] \rightarrow \mathbb{R}$ be given. Then

$$\forall f \in RS(g, [a, b]) \forall c \in (a, b) : f \in RS(g, [a, b]) \wedge f \in RS(g, [c, b]) \wedge \int_a^b f dg = \int_a^c f dg + \int_c^b f dg.$$

Lemma 15.3

Let $f \in RS(g, [a, b])$. Then

$$\{x \in [a, b] : f \text{ discontinuous at } x\} \cap \{x \in [a, b] : g \text{ discontinuous at } x\} = \emptyset.$$

Note. $f \in RS(g, [a, b])$ need not be bounded on intervals where g is constant.

Definition 15.4

We say f is **generalized Stieljes integrable** with respect to g if

$$\exists L \in \mathbb{R} \forall \varepsilon > 0 \exists \delta > 0 \exists \Pi_\varepsilon \text{ unmarked partition } \forall \Pi \text{ marked partition :}$$

$$\|\Pi\| < \delta \wedge \Pi_\varepsilon \subseteq \Pi \Rightarrow |S(f, dg, \Pi) - L| < \varepsilon.$$

Criteria for Stieljes integrability

Theorem 15.5: Reduction to Riemann integral

Let $f, g: [a, b] \rightarrow \mathbb{R}$ be such that

1. f is Riemann integrable and
2. g is continuous on $[a, b]$, differentiable on (a, b) with g' Riemann integrable.

Then

$$f \in RS(g, [a, b]) \quad \wedge \quad \int_a^b f \, dg = \int_a^b f(x)g'(x) \, dx.$$

Proof. Let $\Pi = (\{t_i\}_{i=0}^n, \{t_i^*\}_{i=1}^n)$ be a marked partition of $[a, b]$. For each $i = 1, \dots, n$, let \tilde{t}_i be a point such that $g(t_i) - g(t_{i-1}) = g'(\tilde{t}_i)(t_i - t_{i-1})$ given by the mean value theorem. Let $\tilde{\Pi} = (\{t_i\}_{i=0}^n, \{\tilde{t}_i\}_{i=1}^n)$. Then

$$\begin{aligned} S(f, dg, \Pi) - R(fg', \Pi') &= \sum_{i=1}^n f(t_i^*)(g(t_i) - g(t_{i-1})) - \sum_{i=1}^n f(\tilde{t}_i)g'(\tilde{t}_i)(t_i - t_{i-1}) \\ &= \sum_{i=1}^n [f(t_i^*) - f(\tilde{t}_i)]g'(\tilde{t}_i)(t_i - t_{i-1}). \end{aligned}$$

Note that

$$|\text{RHS}| \leq \|g'\| \sum_{i=1}^n \text{osc}(f, [t_{i-1}, t_i])(t_i - t_{i-1}) \xrightarrow[\|\Pi\| \rightarrow 0]{f g' \text{ RI}} 0.$$

Hence

$$\lim_{\|\Pi\| \rightarrow 0} S(f, g, \Pi) = \lim_{\|\Pi\| \rightarrow 0} R(fg', \Pi) = \int_a^b f g' \, dx.$$

□

Theorem 15.6: BV condition

Let $f, g \in [a, b] \rightarrow \mathbb{R}$ be such that

1. f is continuous and
2. g is of bounded variation ($V(g, [a, b]) < \infty$).

Then $f \in RS(g, [a, b])$ and

$$\left| \int_a^b f \, dg \right| \leq \|f\| V(g, [a, b]).$$

Proof. Let $\Pi = \{t_i\}_{i=0}^n$, $\tilde{\Pi} = \{s_j\}_{j=0}^m$ be unarked partitions of $[a, b]$. Assume $\Pi \subseteq \tilde{\Pi}$ and the set $J_i = \{j = 1, \dots, m : [s_{j-1}, s_j] \subseteq [t_{i-1}, t_i]\}$. Now choose any marked points $t_i^* \in [t_{i-1}, t_i]$ and $s_j^* \in [s_{j-1}, s_j]$. Then

$$\begin{aligned} S(f, dg, \Pi) - S(f, dg, \tilde{\Pi}) &= \sum_{i=1}^n f(t_i^*)(g(t_i) - g(t_{i-1})) - \sum_{j=1}^m f(s_j^*)[g(s_j) - g(s_{j-1})] \\ &= \sum_{i=1}^n \sum_{j \in J_i} [f(t_i^*) - f(s_j^*)][g(s_j) - g(s_{j-1})] \\ &\leq \sum_{i=1}^n \sum_{j \in J_i} \text{osc}(f, [t_{i-1}, t_i]) |g(s_j) - g(s_{j-1})| \\ &\leq \sum_{i=1}^n \text{osc}(f, [t_{i-1}, t_i]) V(g, [t_{i-1}, t_i]). \end{aligned}$$

If f is continuous then f is uniformly continuous. Then

$$\forall \varepsilon > 0 \exists \delta > 0 : \|\Pi\| < \delta \Rightarrow \text{osc}(f, [t_{i-1}, t_i]) < \varepsilon.$$

Then $|\text{RHS}| \leq \varepsilon V(g, [a, b])$. Then for any marked partitions Π, Π' of $[a, b]$ we have

$$\|\Pi\|, \|\Pi'\| < \delta \Rightarrow |S(f, dg, \Pi) - S(f, dg, \Pi')| \leq 2\varepsilon V(g, [a, b]).$$

□

Theorem 15.7: Loéve-Young condition, 1936

Let $f, g : [a, b] \rightarrow \mathbb{R}$ be such that

$$\exists \alpha, \beta \in (0, 1) : f \text{ is } \alpha\text{-Hölder} \wedge g \text{ is } \beta\text{-Hölder} \wedge \alpha + \beta > 1.$$

Then $f \in RS(g, [a, b])$.

Note. f is α -Hölder if

$$\exists C > 0 \forall x, y \in [a, b] : |f(x) - f(y)| \leq C |x - y|^\alpha.$$

16 4.29 Friday Week 5

Wrapping up Stieljes integral

Remark.

- Stieljes integral includes sums:

$$F(x) = \sum_{i=1}^n 1_{[x_i, \infty)} \text{ where } a < x_1 < x_2 < \dots < x_n \leq b.$$

Then for g continuous:

$$\int_a^b g \, dF = \sum_{i=1}^n g(x_i).$$

We can combine these with the *continuous part*:

$$F(x) = \sum_{i=1}^n 1_{[x_i, \infty)}(x) + \int_a^x f(t) dt \Rightarrow \int_a^b b g dF = \sum_{i=1}^r g(x_i) + \int_a^b g(t)f(t) dt.$$

- Standard facts apply:

Lemma 16.1: Integration by parts

If $f \in RS(g, [a, b])$ and $g \in RS(f, [a, b])$ then

$$\int_a^b f dg + \int_a^b g df = fg \Big|_a^b = f(b)g(b) - f(a)g(a).$$

Lemma 16.2: Substitution

If $g \in RS(h, [a, b])$ and $G(x) := \int_a^x g dh$ then

$$f \in RS(G, [a, b]) \Leftrightarrow fg \in RS(h, [a, b])$$

and if (both) true then

$$\int_a^b f dG = \int_a^b fg dh.$$

- The definition is unchanged if f and g are \mathbb{C} -valued. This allows us to define **curve integrals**

$$\int_{\gamma} f(x) dz := \int_0^1 f(\gamma(t)) d\gamma(t)$$

where $\gamma: [0, 1] \rightarrow \mathbb{C}$ continuous.

This is independent of the parametrization.

- We can even generalize this to one of f or g being vector-valued and the other being scalar-valued.
- The length of a curve $\gamma: [a, b] \rightarrow X$ where (X, ρ) is a metric space is given by

$$\text{length}(\gamma) = \sup_{n \geq 1} \sup_{0=t_0 < \dots < t_n=1} \sum_{i=1}^n \rho(\gamma(t_{i-1}), \gamma(t_i)).$$

A curve is **rectifiable** if the length is finite.

If $X = \mathbb{R}^n$ or some other normed space then

$$\rho(\gamma(t_{i-1}), \gamma(t_i)) = \|\gamma(t_i) - \gamma(t_{i-1})\|.$$

This allows us to think of $\text{length}(\gamma)$ as

$$\int_0^1 1 d\|\gamma\|.$$

If γ is differentiable then

$$\gamma(t_i) - \gamma(t_{i-1}) \approx \gamma'(t_{i-1})(t_i - t_{i-1}).$$

Then

$$\text{length}(\gamma) = \int_0^1 \|\gamma'(t)\| dt.$$

Extensions of Riemann-Stieljes theory

Lebesgue integral: The idea is that instead of partitioning the domain of a function, partition the range. This requires developing a theory of measure of rather complicated sets.

Note. f is Lebesgue integrable $\Rightarrow |f|$ is Lebesgue integrable.

This is because Lebesgue integral mimics Darboux's approach.

FTC II does not hold.

The fix is given by:

Definition 16.3

$f: [a, b] \rightarrow \mathbb{R}$ is said to be **Henstock-Kurzweil integrable** if

$$\begin{aligned} \exists L \in \mathbb{R} \forall \varepsilon > 0 \exists \delta: [a, b] \rightarrow (0, \infty) \forall \Pi = (\{t_i\}_{i=0}^n, \{t_i^*\}_{i=1}^n) : \\ \forall i = 1, \dots, n : |t_i - t_{i-1}| < \delta(t_i^*) \Rightarrow |R(f, \Pi) - L| < \varepsilon \end{aligned}$$

where δ is called the **guage function**.

For bounded $f: [a, b] \rightarrow \mathbb{R}$,

$$f \text{ HK-integrable} \Leftrightarrow f \text{ measurable} \wedge f \text{ Lebesgue integrable.}$$

FTC holds: suppose $F: [a, b] \rightarrow \mathbb{R}$ is differentiable on (a, b) . Then F' is HK-integrable and

$$F(b) - F(a) = \int_a^b F'(x) dx.$$

However note that this is restricted to the real line since it uses a partition.

Uniform convergence

Q: Let $\{a_{n,m}\}_{n,m \in \mathbb{N}}$ be real such that

$$\forall m \in \mathbb{N} : b_m := \lim_{n \rightarrow \infty} a_{m,n} \text{ exists}$$

and

$$\forall n \in \mathbb{N} : c_n := \lim_{m \rightarrow \infty} a_{m,n} \text{ exists.}$$

When is $\lim_{n \rightarrow \infty} c_n = \lim_{m \rightarrow \infty} b_m$?

Lemma 16.4

Suppose

$$\forall m \in \mathbb{N} \exists b_m \in \mathbb{R} : \lim_{n \rightarrow \infty} \sup_{n \in \mathbb{N}} |a_{m,n} - b_m| = 0,$$

or that $\lim_{m \rightarrow \infty} a_{m,n}$ is **uniform** in n . Then

$$\forall n \in \mathbb{N} : c_n := \lim_{m \rightarrow \infty} a_{m,n} \text{ exists} \Rightarrow \lim_{m \rightarrow \infty} b_m \text{ and } \lim_{n \rightarrow \infty} c_n \text{ exist} \wedge \lim_{n \rightarrow \infty} c_n = \lim_{m \rightarrow \infty} b_m.$$

This means

$$\lim_{n \rightarrow \infty} \lim_{m \rightarrow \infty} a_{m,n} = \lim_{m \rightarrow \infty} \lim_{n \rightarrow \infty} a_{m,n}.$$