

NORTHWESTERN UNIVERSITY



REAL ANALYSIS

MATH 321-2

uniform continuity go brrrr

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1 The Riemann Stieljis Integral

Remark 1.1. For this section, let there be a standing assumption that f is bounded.

Definition 1.2. Let $[a, b]$ be a given interval. A **partition** P of $[a, b]$ is a finite set of points $\{x_0, x_1, \dots, x_n\}$ where

$$a = x_0 \leq x_1 \leq \dots \leq x_n = b.$$

We will adopt the following notation: $\Delta x_i = x_i - x_{i-1}$. Now, let P be any partition of $[a, b]$. We put

1. $M_i = \sup f(x) \quad (x_{i-1} \leq x \leq x_i),$
2. $m_i = \inf f(x) \quad (x_{i-1} \leq x \leq x_i),$
3. $U(P, f) = \sum_{i=1}^n M_i \Delta x_i,$
4. $L(P, f) = \sum_{i=1}^n m_i \Delta x_i,$

and finally obtain the *upper* and *lower Riemann integrals* of f over $[a, b]$:

1. $\overline{\int_a^b} f dx = \inf_{P \in \mathcal{P}} U(P, f),$
2. $\underline{\int_a^b} f dx = \sup_{P \in \mathcal{P}} L(P, f)$

where \mathcal{P} is the set of all partitions P of $[a, b]$.

Lemma 1.3

The set $\{U(P, f) \mid P \in \mathcal{P}\}$ is bounded below.

Proof. Since f is bounded, $f(x) \geq m$ for all $x \in [a, b]$. Notice that

$$U(P, f) = \sum_{i=1}^n \sup_{x \in [x_{i-1}, x_i]} f(x) \Delta x_i \geq \sum_{i=1}^n m \cdot \Delta x_i = m(b-a).$$

□

Definition 1.4. We say that f is **Riemann-integrable** and write $f \in \mathcal{R}([a, b])$ if

$$\overline{\int_a^b} f dx = \underline{\int_a^b} f dx.$$

Remark 1.5. Notice that $L(P, f)$ and $U(P, f)$ are bounded by $m(b-a)$ and $M(b-a)$, where $m \leq f(x) \leq M$ for all $x \in [a, b]$. In other words, the upper and lower integrals exist for *every* bounded real function.

Definition 1.6. Let α be nondecreasing (monotonically increasing) function on $[a, b]$. We write $\Delta \alpha_i = \alpha(x_i) - \alpha(x_{i-1})$. (Clearly, $\Delta \alpha_i \geq 0$. We put

1. $U(P, f, \alpha) = \sum_{i=1}^n M_i \Delta \alpha_i,$
2. $L(P, f, \alpha) = \sum_{i=1}^n m_i \Delta \alpha_i.$

where M_i, m_i have the same meaning as in Definition 1.2 and we define

$$\overline{\int_a^b} f d\alpha = \inf_{P \in \mathcal{P}} U(P, f, \alpha) \quad (1)$$

and

$$\underline{\int_a^b} f d\alpha = \sup_{P \in \mathcal{P}} L(P, f, \alpha). \quad (2)$$

If (1) and (2) are equal, then we say f is *integrable with respect to α over $[a, b]$* , written $f \in \mathcal{R}(\alpha)$, and notate their common value, known as the **Riemann-Stieltjes integral** as

$$\int_a^b f d\alpha.$$

Question 1.7. When is $f \in \mathcal{R}(\alpha)$

It may be helpful to rephrase the question to ask when f is *not* in $\mathcal{R}(\alpha)$.

- Nonexample: The function

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

is *not* in $\mathcal{R}([a, b])$. Notice that for any partition P , $U(P, f) = 1 \neq 0 = L(P, f)$.

So whenever $\inf_{P \in \mathcal{P}} U(P, f, \alpha)$ is *strictly* greater than $\sup_{P \in \mathcal{P}} L(P, f, \alpha)$, we know $f \notin \mathcal{R}(\alpha)$.

Definition 1.8. For partitions $P, Q \in \mathcal{P}$,

1. If $Q \supset P$, we say Q is a **refinement** of P .
2. We call $P^* = P \cup Q$ a **common refinement**.

Lemma 1.9

If $Q \supset P$, then $U(Q, f, \alpha) \leq U(P, f, \alpha)$ and $L(Q, f, \alpha) \geq L(P, f, \alpha)$.

Proof. Let $Q = P \cup \{x_0, \dots, x_k\}$. If $k = 0$, the conclusion obviously holds. Now, suppose $k \in \mathbb{N}$ and $U(Q, f, \alpha) \leq U(P, f, \alpha)$, and let P^* contain just one more point than P , x^* , where $x_{i-1} < x^* < x_i$. Write $w_1 = \sup_{x_{i-1} \leq x \leq x^*} f(x)$ and $w_2 = \sup_{x^* \leq x \leq x_i} f(x)$. Notice $w_1, w_2 \leq M_i$ where $M_i = \sup_{x_{i-1} \leq x \leq x_i} f(x)$. Then

$$\begin{aligned} U(P, f, \alpha) - U(P^*, f, \alpha) &= M_i[\alpha(x_i) - \alpha(x_{i-1}) - w_1[\alpha(x^*) - \alpha(x_{i-1})] - w_2[\alpha(x_i) - \alpha(x^*)]] \\ &= (M_i - w_1)[\alpha(x^*) - \alpha(x_{i-1})] + (M_i - w_2)[\alpha(x_i) - \alpha(x^*)] \\ &\geq 0. \end{aligned}$$

The proof for the lower integrals is the same. □

Remark 1.10. Notice that for any partitions P_1, P_2 , it follows with the common refinement $P^* = P_1 \cup P_2$ that

$$L(P_1, f, \alpha) \leq L(P^*, f, \alpha) \leq U(P^*, f, \alpha) \leq U(P_2, f, \alpha).$$

Corollary 1.11

$$\int_a^b f d\alpha \leq \overline{\int_a^b f d\alpha}.$$

We now arrive at a useful lemma relating integrability to being able to find partitions that allow the distance between upper and lower integrals to be arbitrarily small:

Lemma 1.12

$f \in \mathcal{R}(\alpha)$ if, and only if, $\forall \epsilon > 0$, there exists a partition P such that $U(P, f, \alpha) - L(P, f, \alpha) < \epsilon$.

Proof. Let $f \in \mathcal{R}$. Then there exists a partition P_1 such that $0 \leq U(P_1, f, \alpha) - \overline{\int_a^b f d\alpha} < \epsilon/2$. Similarly, there exists P_2 such that $0 \leq \underline{\int_a^b f d\alpha} - L(P_2, f, \alpha) < \epsilon/2$. (Notice that $f \in \mathcal{R}(\alpha)$, so $\overline{\int_a^b f d\alpha} = \underline{\int_a^b f d\alpha} = \int_a^b f d\alpha$.) Let $P = P_1 \cup P_2$ be the common refinement of P_1 and P_2 . Then

$$U(P, f, \alpha) \leq U(P_1, f, \alpha) < \int_a^b f d\alpha + \epsilon/2 < L(P_2, f, \alpha) + \epsilon \leq L(P, f, \alpha) + \epsilon.$$

Now assume the converse. Recall that $\overline{\int_a^b f d\alpha} \leq U(P, f, \alpha)$ and $\underline{\int_a^b f d\alpha} \geq L(P, f, \alpha)$ for any partition P . Let $\epsilon > 0$. Then there exists a partition P such that

$$0 \leq \overline{\int_a^b f d\alpha} - \underline{\int_a^b f d\alpha} \leq U(P, f, \alpha) - L(P, f, \alpha) < \epsilon.$$

□

Now, let's introduce a bit of notation to make our lives easier. We can write that f is continuous on a metric space X as $f \in \mathcal{C}(X)$. Furthermore, we can improve upon our notation of integrability to write $f \in \mathcal{R}(\alpha, S)$ to mean that f is integrable on with respect to α over S .

Theorem 1.13

Let $f \in \mathcal{C}([a, b])$. Then $f \in \mathcal{R}(\alpha, [a, b])$.

Proof. Notice $[a, b]$ is compact. Thus f is uniformly continuous on $[a, b]$, so for $\epsilon > 0$, there exists $\delta > 0$ such that $|f(x) - f(y)| < \frac{\epsilon}{\alpha(b) - \alpha(a)}$ whenever $|x - y| < \delta$. Now, pick a partition P (with n elements) such that $\Delta x_j < \delta$ for all j . Then

$$\begin{aligned} \overline{\int_a^b f d\alpha} - \underline{\int_a^b f d\alpha} &\leq U(P, f, \alpha) - L(P, f, \alpha) = \sum_{j=1}^n \sup_{I_j} f \Delta x_j - \sum_{j=1}^n \inf_{I_j} f \Delta x_j \\ &= \sum_{j=1}^n \left(\sup_{I_j} f - \inf_{I_j} f \right) \Delta x_j \\ &< \sum_{j=1}^n \frac{\epsilon}{\alpha(b) - \alpha(a)} \Delta x_j \\ &= \frac{\epsilon}{\alpha(b) - \alpha(a)} (\alpha(b) - \alpha(a)) = \epsilon. \end{aligned}$$

Since ϵ is arbitrary, the proof is complete. □

Remark 1.14. It turns out, we need not require that f is continuous on the entire interval; it suffices for f to be continuous *except at finitely many points*, with α continuous where f is not! Zoo wee mama!

Remark 1.15. In fact, the **Lebesgue Criterion for Riemann Integrability** states that

$$f \in \mathcal{R} \iff f \text{ is discontinuous on a set of measure zero!}$$

(As a reminder, a set E has measure zero if for $\epsilon > 0$, there exists a collection of intervals $\{I_n\} \supset E$ such that $\sum_n \text{diam}(I_n) < \epsilon$.)

Theorem 1.16 (The cooler Daniel)

If f is continuous at except finitely many points and α is continuous at the points of f 's discontinuity, then $f \in \mathcal{R}(\alpha)$.

Proof. Let f be continuous except at finitely many points, say $\{x_0, \dots, x_n\}$. Because f is continuous at except *finitely* many points, we can let $M = |f|$.

Since the set of discontinuities $S = \{x_0, \dots, x_n\}$ is finite, α is uniformly continuous on S . It follows from the triangle inequality and the monotone increasing property of α that for all $\epsilon > 0$ there exists a $\delta > 0$ such that $\alpha(x_j + \delta) - \alpha(x_j - \delta) < \epsilon$.

We can always choose δ to be smaller, so without loss of generality, assume the set of $[x_j - \delta, x_j + \delta]$ is disjoint. Let $F = [a, b] \setminus \bigcup_{i=1}^n (x_j - \delta, x_j + \delta)$. F is compact, so for all $\epsilon > 0$, there exists $\delta' > 0$ such that $|f(u) - f(v)| < \epsilon$ for all $u, v \in F$ where $|u - v| < \delta'$.

We can now partition F into intervals I_j with $\Delta x_j < \delta'$. Let $J_i = [x_i - \delta, x_i + \delta]$. We can now partition $[a, b]$ into a partition P consisting of the I_i 's and J_i 's. Then

$$\begin{aligned} \overline{\int} f d\alpha - \underline{\int} f d\alpha &\leq \sum_j \sup_{I_j} f \Delta x_j - \sum_j \inf_{I_j} f \Delta x_j + \sum_j \sup_{J_j} f \Delta x_j - \sum_j \inf_{J_j} f \Delta x_j \\ &= \sum_j \left(\sup_{I_j} f - \inf_{I_j} f \right) \Delta x_j + \sum_j \left(\sup_{J_j} f - \inf_{J_j} f \right) \Delta x_j \\ &\leq \epsilon \sum_j \Delta x_j + \sum_j 2M\epsilon \\ &= K\epsilon, \end{aligned}$$

where $K \in \mathbb{R}$. □

Remark 1.17. What if we want to compose functions? Will their composition be integrable? Well it turns out that if the inner function is integrable, then the outer function being continuous on the range of the inner function is sufficient for integrability of the composition.

Theorem 1.18 (Integrability of composition of functions)

If f takes values in $[m, M]$ on $[a, b]$, $f \in \mathcal{R}(\alpha, [a, b])$, and ϕ continuous on $[m, M]$, then $\phi \circ f \in \mathcal{R}(\alpha, [a, b])$.

The proof for this theorem is pretty funny, so hang on.

Proof. ϕ is uniformly continuous on $[m, M]$ (why?) so for some $\epsilon > 0$ there exists a $\delta < \epsilon$ such that $|\phi(u) - \phi(v)| < \epsilon$ whenever $|u - v| < \delta$. Note that if we find a sufficiently small δ , then any value less than δ

also works so we can restrict ourselves to only working with $\delta < \epsilon$. It turns out, this restriction will become very useful later on!

Since $f \in \mathcal{R}(\alpha)$, it follows from **Lemma 1.12** that there exists a partition P such that

$$U(P, f, \alpha) - L(P, f, \alpha) < \delta^2.$$

For each $j = 1, \dots, n$ (where $n = |P|$), if $\sup_{I_j} f - \inf_{I_j} f < \delta$, place $j \in A$. Otherwise place $j \in B$.

1. If $j \in A$, then $|\phi(f(x)) - \phi(f(y))| < \epsilon$, $x, y \in I_j$.
2. If $j \in B$, then $\sup_{I_j}(\phi \circ f) - \inf_{I_j}(\phi \circ f) \leq 2 \sup_{[m, M]} |\phi|$, and let's notate $K = \sup_{[m, M]} |\phi|$.
But $U(P, f, \alpha) - L(P, f, \alpha) < \delta^2$, so

$$\sum_{j \in B} \delta \Delta \alpha_j \leq \sum \left(\sup_{I_j} f - \inf_{I_j} f \right) \Delta x_j \leq \delta^2.$$

Dividing both sides by δ , we get $\sum_{j \in B} \Delta \alpha_j < \delta$.

Thus

$$\begin{aligned} \overline{\int} \phi \circ f d\alpha - \underline{\int} \phi \circ f d\alpha &\leq U(P, \phi \circ f, \alpha) - L(P, \phi \circ f, \alpha) \\ &\leq \sum_{j=1}^n \epsilon \Delta \alpha_j + \sum_{j \in B} 2K \Delta \alpha_j \\ &\leq \epsilon(\alpha(b) - \alpha(a)) + 2K\delta \\ &< \epsilon(\alpha(b) - \alpha(a) + 2K). \end{aligned}$$

□

Remark 1.19. Note that we (stupidly, in the words of Jared Wunsch,) overcount in the third-to-last line of the extended equation; summing over *all* j instead of just $j \in A$.

Remark 1.20. You've probably caught on to the style of proving a function is integrable: find a partition such that the difference $U - L$ is bounded above by an arbitrary ϵ .

We will now explore the properties of the integral, which pretty much agree with the intuition of someone who studied linear algebra and multivariate calculus with Aaron Peterson in MATH 291 @ Northwestern University:

1. The integral is *linear* over \mathbb{R} ;
2. If a function bounds another from above, then the integral of the first will bound the integral of the second from above;
3. We can split integrals by an intermediate bound;
4. If the magnitude of a function is bounded by a finite number M , then the magnitude of the integral of that function will be bounded by the product of M and the width of the integral's bounds.
5. The sum of functions integrable with respect to different "clock speeds" is integrable with respect to the sum of their individual clock speeds. (Really pushing the metaphor here..)

Theorem 1.21 (Rudin 6.12)

1. If $f_1, f_2 \in \mathcal{R}(\alpha)$ then $f_1 + f_2 \in \mathcal{R}(\alpha)$, $cf \in \mathcal{R}(\alpha)$ for every $c \in \mathbb{R}$, and

$$\int_a^b (f_1 + f_2) d\alpha = \int_a^b f_1 d\alpha + \int_a^b f_2 d\alpha \quad \text{and} \quad \int_a^b cf d\alpha = c \int_a^b f d\alpha.$$

2. If $f_1(x) \leq f_2(x)$ on $[a, b]$, then

$$\int_a^b f_1 d\alpha \leq \int_a^b f_2 d\alpha.$$

3. If $f \in \mathcal{R}(\alpha)$ on $[a, b]$ and $a < c < b$, then $f \in \mathcal{R}(\alpha)$ on $[a, c]$ and $[c, b]$, and

$$\int_a^c f d\alpha + \int_c^b f d\alpha = \int_a^b f d\alpha.$$

4. If $f \in \mathcal{R}(\alpha)$ on $[a, b]$ and if $|f(x)| \leq M$ on $[a, b]$, then

$$\left| \int_a^b f d\alpha \right| \leq M[\alpha(b) - \alpha(a)];$$

5. If $f \in \mathcal{R}(\alpha_1)$ and $f \in \mathcal{R}(\alpha_2)$, then $f \in \mathcal{R}(\alpha_1 + \alpha_2)$ and

$$\int_a^b f d(\alpha_1 + \alpha_2) = \int_a^b f d\alpha_1 + \int_a^b f d\alpha_2;$$

If $f \in \mathcal{R}(\alpha)$ and $c \in \mathbb{R}^+$, then $f \in \mathcal{R}(c\alpha)$ and

$$\int_a^b f d(c\alpha) = c \int_a^b f d\alpha.$$

Proof. The proofs for each part are very similar, so we will only prove (1). However Wunsch messed up here so we'll skip this for now. A proof is in Rudin if you really want to read it. \square

The previous theorem (**Rudin 6.12**) gives us a lot of power to determine the integrability of functions; we just need to be adept at manipulating expressions into sums and compositions of continuous functions. Thankfully, $x \rightarrow x^2$ is continuous and we have a useful identity to translate multiplication into addition:

A useful identity: $xy = \frac{1}{4}((x+y)^2 - (x-y)^2).$

Theorem 1.22

Let $f, g \in \mathcal{R}(\alpha)$. Then

1. $fg \in \mathcal{R}(\alpha)$,
2. $|f| \in \mathcal{R}(\alpha)$, and
3. $\left| \int_a^b f d\alpha \right| \leq \int_a^b |f| d\alpha.$

Proof. Notice that $f \pm g \in \mathcal{R}(\alpha)$, so $(f \pm g)^2 \in \mathcal{R}(\alpha)$. Then

$$fg = \frac{1}{4} ((f+g)^2 - (f-g)^2) \in \mathcal{R}(\alpha).$$

Since $u \rightarrow u^2$ is continuous, $|f| \in \mathcal{R}(\alpha)$. Finally, there exists a $c = \pm 1$ where

$$\left| \int f d\alpha \right| = c \int f d\alpha = \int cf d\alpha \leq \int |f| d\alpha.$$

□

Example 1.23 (Heaviside Function)

We define the **Heaviside Function** as

$$H(x) = \begin{cases} 0 & x \leq 0 \\ 1 & x > 0 \end{cases}$$

If $a < 0 < b$ and f is continuous at $x = 0$, then $f \in \mathcal{R}([a, b], H)$ and $\int_a^b f dH = f(0)$.

Proof. Again, we choose a funny partition that will result in some clean shit: Let $P = \{x_0, x_1, x_2, x_3\}$, where $x_0 = a, x_1 = 0, x_3 = b$, and $x_2 \in (0, b)$. Then

$$\begin{aligned} U(P, f, H) &= \sup_{[a, 0]} f \cdot (H(0) - H(a)) + \sup_{[0, x_2]} f \cdot (H(x_2) - H(0)) + \sup_{[x_2, b]} f \cdot (H(b) - H(x_2)) \\ &= \sup_{[a, 0]} f \cdot (0 - 0) + \sup_{[0, x_2]} f \cdot (1 - 0) + \sup_{[x_2, b]} f \cdot (1 - 1) \\ &= \sup_{[0, x_2]} f. \end{aligned}$$

Similarly, $L(P, f, H) = \inf_{[0, x_2]} f$. Letting x_2 approach 0 from the right, notice that $U(P, f, H) \rightarrow f(0)^+$ and $L(P, f, H) \rightarrow f(0)^-$. So $\int_a^b f dH = 0$. □

Corollary 1.24 (Basically Heaviside, with **linearity!**)

Let $\alpha = \sum_{j=1}^N c_j H(x - s_j)$, $s \in [a, b]$, and $f \in \mathcal{C}([a, b])$. Then

$$\int_a^b f d\alpha = \sum_{i=1}^N c_i f(s_i)$$

Proof. Immediate by Theorem 1.20. □

Remark 1.25. Rudin extends α to be an infinite sum, but we don't need to get that crazy here...

Theorem 1.26

Say α' exists for all $x \in [a, b]$, α' is bounded, and f is *Riemann*-integrable (i.e. $f \in \mathcal{R}([a, b], x)$). Then $f \in \mathcal{R}(\alpha)$. If $\alpha' \in \mathcal{R}([a, b], x)$, then $\int_a^b f d\alpha = \int_a^b f(x) \alpha'(x) dx$.

Proof. Let α' be bounded for all $x \in [a, b]$ and $f \in \mathcal{R}([a, b], x)$. For $\epsilon > 0$, there exists a partition P of $[a, b]$ such that $U(P, f) - L(P, f) < \epsilon/K$, where $K = \sup_{[a, b]} \alpha'$. Now, note that for any $j \in P$, the Mean Value Theorem implies there exists some $x_j^* \in [x_{j-1}, x_j]$ such that $\alpha(x_j) - \alpha(x_{j-1}) = \alpha'(x_j^*)\Delta x_j$. With this, notice

$$\begin{aligned} U(P, f, \alpha) - L(P, f, \alpha) &= \sum_{j \in P} \left(\sup_{I_j} f - \inf_{I_j} f \right) (\alpha(x_j) - \alpha(x_{j-1})) \\ &= \sum_{j \in P} (M_j - m_j) \alpha'(x_j^*) \Delta x_j \\ &\leq K \sum_{j \in P} (M_j - m_j) \Delta x_j \\ &< K \cdot \epsilon/K = \epsilon. \end{aligned}$$

Thus $f \in \mathcal{R}(\alpha)$. Now, let $\alpha' \in \mathcal{R}([a, b], x)$. Then for $\epsilon > 0$, there exists a partition P such that

1. $U(P, f) - L(P, f) < \epsilon$,
2. $U(P, f, \alpha') - L(P, f, \alpha') < \epsilon$,
3. $\sum_{j \in P} (\sup_{I_j} \alpha' - \inf_{I_j} \alpha') \Delta x_j < \epsilon$, or $U(P, \alpha') - L(P, \alpha') < \epsilon$, and
4. $U(P, f, \alpha) - L(P, f, \alpha) < \epsilon$, shown earlier in the proof.

Now, for each $j \in P$ pick any $u_j \in I_j$. By the Mean Value Theorem, there exists some $x_j^* \in I_j$ such that

$$\sum_{j \in P} f(u_j) \Delta \alpha_j = \sum_{j \in P} f(u_j) \alpha'(x_j^*) \Delta x_j = \left(\sum_{j \in P} f(u_j) \alpha'(u_j) \Delta x_j \right) + \left(\sum_{j \in P} f(u_j) (\alpha'(x_j^*) - \alpha'(u_j)) \Delta x_j \right).$$

Define, for sake of brevity, $A = \sum_{j \in P} f(u_j) \alpha'(u_j) \Delta x_j$ and $B = \sum_{j \in P} f(u_j) (\alpha'(x_j^*) - \alpha'(u_j)) \Delta x_j$. (These are the last two sums in the previous equation.) Letting $M = \sup |f|$, we can bound B as follows:

$$|B| \leq \sum_{j \in P} \sup |f| \cdot \left(\sup_{I_j} \alpha' - \inf_{I_j} \alpha' \right) \Delta x_j \leq M\epsilon.$$

Since $L(P, f, \alpha) \leq A + B \leq U(P, f, \alpha)$, we have $L(P, f, \alpha) - M\epsilon \leq A \leq U(P, f, \alpha) + M\epsilon$, and thus

$$A - \int_a^b f d\alpha < \epsilon + M\epsilon.$$

Since A is a Riemann Sum, we also have

$$\left| A - \int_a^b f \alpha' dx \right| < \epsilon.$$

Combining all our Pokémon card inequality cards collected throughout the proof, we finally get

$$\left| \int_a^b f d\alpha - \int_a^b f \alpha' dx \right| < \epsilon + M\epsilon + \epsilon.$$

□

2 Integration and Differentiation

We will explore the dynamics between integration and differentiation, and as expected, the two act as quasi-inverse functions.

Theorem 2.1 (Fundamental Theorem of Calculus 1)

Let $f \in \mathcal{R}([a, b])$ and f be continuous at a point $x_0 \in [a, b]$. Then

$$f(x_0) = \left. \frac{d}{dx} \int_a^x f(s) ds \right|_{x=x_0}.$$

Proof. Differentiating our funny integral, we have that

$$\frac{d}{dx} \int_a^x f(s) ds = \lim_{h \rightarrow 0} \frac{\int_0^{x_0+h} f(s) ds - \int_a^{x_0} f(s) ds}{h}.$$

We now have to inspect both right and left hand limits, but as the proofs for each case are analogous, we'll just look at the right hand limit: $h \rightarrow 0^+$. Since f is continuous at x_0 , for $\epsilon > 0$, there exists $\delta > 0$ such that if $0 \leq |y - x_0| < \delta$, then $|f(y) - f(x_0)| < \epsilon$. Since we're taking the limit as h approaches 0, we can limit our choice of h to only those with $h < \delta$. Pick any of them. Then $|f(s) - f(x_0)| < \epsilon$ for all $s \in (x_0, x_0 + h)$.

We'll now employ a slick trick: since $f(x_0)$ is constant, we can write $f(x_0) = \frac{1}{h} \int_{x_0}^{x_0+h} f(x_0) ds$.

Then

$$\begin{aligned} \left| \frac{1}{h} \int_{x_0}^{x_0+h} f(s) ds - f(x_0) \right| &= \left| \frac{1}{h} \int_{x_0}^{x_0+h} f(s) ds - \frac{1}{h} \int_{x_0}^{x_0+h} f(x_0) ds \right| \\ &= \left| \frac{1}{h} \int_{x_0}^{x_0+h} (f(s) - f(x_0)) ds \right| \\ &\leq \frac{1}{h} \int_{x_0}^{x_0+h} |f(s) - f(x_0)| ds \\ &< \frac{1}{h} \int_{x_0}^{x_0+h} \epsilon ds \\ &= \epsilon. \end{aligned}$$

□

Remark 2.2. Notice that $F(x) = \int_a^x f(s) ds$ is continuous on $[a, b]$.

Proof. By continuity, if $x < y$ then

$$|F(x) - F(y)| = \left| \int_x^y f(s) ds \right| \leq \int_x^y |f(s)| ds \leq \sup |f| (y - x).$$

So for $\epsilon > 0$, take $\delta = \epsilon / \sup |f|$.

□

Continuous things have antiderivatives!

Theorem 2.3 (Fundamental Theorem of Calculus 2 (le célèbre))

Let $f \in \mathcal{R}([a, b])$, and there exist a differentiable F such that $F' = f$ on $[a, b]$. Then

$$\int_a^b f(s) ds = F(b) - F(a).$$

Remark 2.4. Recall that integrable functions need not be continuous. (What's an example of a finitely discontinuous function that is Riemann-integrable?) However, the large majority of commonly used integrable functions are continuous, so we'll prove this theorem for continuous functions first, and then weaken our hypothesis for the *real* proof.

Proof. (naive) Let f be continuous, and set $G(x) = \int_c^x f(s) ds$. By FTC1,

$$\frac{d}{dx}G(x) = f(x) = F'(x),$$

so $G(x) = F(x) + C$, where C is constant. Thus

$$\int_a^b f(s) ds = \int_c^b f(s) ds - \int_c^a f(s) ds = G(b) - G(a) = F(b) - F(a).$$

□

Proof. (The real one..) You know the drill: For $\epsilon > 0$, there exists a partition $P = \{x_0, x_1, \dots, x_n\}$ such that $U(P, f) - L(P, f) < \epsilon$. By the Mean Value Theorem, there exists a $x_j^* \in [x_{j-1}, x_j]$ such that $F(x_j) - F(x_{j-1}) = f(x_j^*)\Delta x_j$. Then

$$F(b) - F(a) = \sum_{i=1}^n F(x_i) - F(x_{i-1}) = \sum_{i=1}^n f(x_i^*)\Delta x_i.$$

Thus,

$$\left| F(b) - F(a) - \int_a^b f(s) ds \right| < \epsilon.$$

□

We now approach the topic of **integration by parts**, which is often thought of as a computational integration tool by calculus students. As it turns out, it also carries much importance in analysis by showing that one can move derivatives around inside the integrand at the cost of a negative sign:

Theorem 2.5 (Integration by Parts)

Say F, G are differentiable functions, $F' = f$, $G' = g$, and $f, g \in \mathcal{R}$. Then

$$\int_a^b Fg dx = FG \Big|_a^b - \int_a^b fG dx.$$

Proof. By the chain rule, $(FG)' = Fg + fG$. Rearrange to isolate Fg and apply FTC2.

□

Corollary 2.6

If $G = 0$ and a, b , then $\int_a^b FG' dx = - \int_a^b F'G dx$.

Finally, we introduce machinery that will facilitate changing the bounds of integration. In doing so, we must account for the "stretch" factor when stretching or shrinking the region of integration.

Theorem 2.7 (Change of Variables)

Let $\phi : [a, b] \rightarrow [A, B]$ be strictly increasing, where $\phi(a) = A$ and $\phi(b) = B$. Let ϕ be differentiable, with $\phi' \in \mathcal{R}$, and $f : [A, B] \rightarrow \mathbb{R}$ be continuous. Then

$$\int_a^b f(\phi(x))\phi'(x) dx = \int_A^B f(y) dy.$$

Proof. Set $F(x) = \int_A^x f(s) ds$. By FTC1, $F' = f$. By the chain rule, $\frac{d}{dx}F(\phi(x)) = f(\phi(x))\phi'(x)$. By FTC2, we have

$$\int_a^b f(\phi(x))\phi'(x) dx = \frac{d}{dx} \int_a^b F(\phi(x)) = F(\phi(x)) \Big|_a^b = \int_A^B f(s) ds.$$

□

2.1 Appendix

There are some arguments utilized throughout the section worth having in writing for posterity:

Theorem 2.8

Recall that $F \in \mathcal{R}(\alpha)$ on $[a, b]$ if and only if for every $\epsilon > 0$ there exists a partition P such that

$$U(P, f, \alpha) - L(P, f, \alpha) < \epsilon. \quad (3)$$

It is now the case that

1. If (3) holds for some P and ϵ , then (3) holds (with the same ϵ) for *every* refinement of P .
2. If (3) holds for $P = \{x_0, \dots, x_n\}$ and if s_i, t_i are arbitrary points in $[x_{i-1}, x_i]$, then

$$\sum_{i=1}^n |f(s_i) - f(t_i)| \Delta \alpha_i < \epsilon.$$

3. If $f \in \mathcal{R}(\alpha)$ and the hypothesis of (2) hold, then

$$\left| \sum_{i=1}^n f(t_i) \Delta \alpha_i - \int_a^b f d\alpha \right| < \epsilon.$$

Proof. Immediate after noting $\sum_{i=1}^n |f(s_i) - f(t_i)| \Delta x_i \leq U(P, f, \alpha) - L(P, f, \alpha)$,

$$L(P, f, \alpha) \leq \sum f(t_i) \Delta \alpha_i \leq U(P, f, \alpha) \quad \text{and} \quad L(P, f, \alpha) \leq \int f d\alpha \leq U(P, f, \alpha).$$

□

Theorem 2.9

If f is monotonic on $[a, b]$ and α is continuous on $[a, b]$, then $f \in \mathcal{R}(\alpha)$.

Proof. Monotonic functions are discontinuous at most countably many times. Countable subsets have measure zero, so we're done. Thanks, Lebesgue! \square

3 Sequences and Series of Functions

Say $f_n : E \rightarrow \mathbb{C}$ are functions.

Definition 3.1. The sequence $\{f_n\}$ **converges pointwise** on E (to $f(x)$) if for all $x \in E$,

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

Question 3.2. What good properties of f_n might f inherit?

LMAO none. Anyway, an example:

Example 3.3

Let $f_n = \arctan(nx) \in \mathbb{R}$. f_n converges pointwise to

$$f(x) = \begin{cases} -\pi/2 & x < 0 \\ 0 & x = 0 \\ \pi/2 & x > 0. \end{cases}$$

So f_n is infinitely differentiable, but $\lim_{n \rightarrow \infty} f(n)$ is not even continuous!

Definition 3.4. f_n **converges uniformly** on E if for all $\epsilon > 0$, there exists an $N \in \mathbb{N}$ such that if $n \geq N$ and $x \in E$, then

$$|f_n - f(x)| < \epsilon.$$

Remark 3.5. N is *independent* of x ! (What else does this independence remind you of?)

Example 3.6 (3.3, revisited.)

Pick $\epsilon = \frac{\pi}{4}$. Given N , there exists $x > 0$ such that $\arctan(Nx) < \frac{\pi}{4}$ (since $\lim_{n \rightarrow \infty} \arctan(Nx) = 0$). Then

$$|f_N(x) - f(x)| < \frac{\pi}{4}.$$

Theorem 3.7 (Cauchy Criterion for sequences of functions, kinda.)

$f_n \rightarrow f$ uniformly on E if, and only if, for every $\epsilon > 0$, there exists an $N \in \mathbb{N}$ such that for $m, n \geq N$, for all $x \in E$,

$$|f_m(x) - f_n(x)| < \epsilon.$$

Proof. Say $f_n \rightarrow f$ uniformly. Then for $\epsilon > 0$, there exists $N \in \mathbb{N}$ such that for all $n \geq N$, $|f_n(x) - f(x)| < \frac{\epsilon}{2}$ for all x . Then for $m \geq N$, we obtain the same inequality and the proof follows directly from the triangle inequality. Conversely, suppose for every $\epsilon > 0$, there exists $N \in \mathbb{N}$ such that for $m, n \geq N$, for all $x \in E$, $|f_m(x) - f_n(x)| < \frac{\epsilon}{2}$. Then for all x , if we fix m , $\{f_n(x)\}$ is Cauchy in \mathbb{C} . By completeness of \mathbb{C} , there exists a $f(x)$ such that $\lim_{n \rightarrow \infty} f_n(x) = f(x)$. By uniform convergence, for all $m \geq N$

$$\lim_{n \rightarrow \infty} |f_m(x) - f_n(x)| = |f_m(x) - f(x)| \leq \frac{\epsilon}{2}.$$

□

Theorem 3.8

If f_n are continuous functions on X , a metric space, and $f_n \rightarrow f$ uniformly on X , then f is continuous.

Proof. Fix $y \in X$. Then for $\epsilon > 0$:

1. There exists $N \in \mathbb{N}$ such that $|f_n(x) - f(x)| < \frac{\epsilon}{3}$ for all $n \geq N$ and $x \in X$.
2. If f_N continuous, there exists $\delta > 0$ such that $|f_N(x) - f_N(y)| < \frac{\epsilon}{3}$ whenever $d(x, y) < \delta$.

Now for all x such that $d(x, y) < \delta$, (1) and (2) give

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

□

We will now introduce an important notion of distance between functions, which will nicely lead to the notion of a metric space of continuous functions!

Definition 3.9. If $f : X \rightarrow \mathbb{C}$ is bounded, set $\|f\| = \sup |f|$, where X is a nonempty metric space. Let

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

For $f, g \in \mathcal{C}(X)$, we define $d_{\mathcal{C}}(f, g) = \|f - g\|$.

Of course, we wouldn't be defining a distance function if we didn't think we could use it as a metric...

Lemma 3.10

$$\|f + g\| \leq \|f\| + \|g\|.$$

Proof. As one would intuitively expect,

$$\|f + g\| = \sup |f(x) + g(x)| \leq \sup (|f(x)| + |g(x)|) \leq \sup |f| + \sup |g| = \|f\| + \|g\|.$$

□

Proposition 3.11

$d_{\mathcal{C}}$ is a metric on $\mathcal{C}(X)$.

Proof. Using the lemma,

- $d_{\mathcal{C}}$ is symmetric since $|f - g| = |g - f|$.
- $d_{\mathcal{C}}(f, g) = 0 \iff \sup |f - g| = 0 \iff |f(x) - g(x)| = 0 \quad \forall x \iff f = g$.
- $d(f, h) = \|f - h\| = \|f - g + g - h\| \leq \|f - g\| + \|g - h\| = d(f, g) + d(g, h)$.

□

Sick, so $(\mathcal{C}(X), d_{\mathcal{C}})$ is a metric space.

But what's the point of going through all this work to verify this fact?

Proposition 3.12 (Convergence in $(\mathcal{C}(X), d_{\mathcal{C}})$ is analogous to uniform convergence of functions.)

$f_n \rightarrow f$ in $\mathcal{C}(X)$ if, and only if, $f_n \rightarrow f$ uniformly.

Proof. Let $f_n \rightarrow f$ in $\mathcal{C}(X)$. Then for $\epsilon > 0$, there exists $N \in \mathbb{N}$ such that

$$\sup |f(x) - f_n(x)| = \|f_n - f\| < \epsilon$$

whenever $n \geq N$. Thus, $|f(x) - f_n(x)| < \epsilon$ for all x . Conversely, let $f_n \rightarrow f$ uniformly. Then for $\epsilon > 0$, there exists $N \in \mathbb{N}$ such that if $n \geq N$, $x \in X$, then

$$|f_n(x) - f(x)| < \frac{\epsilon}{2},$$

so

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

□

Theorem 3.13 (this seems important)

$\mathcal{C}(X)$ is complete.

Proof. Say $\{f_n\}$ is Cauchy in $\mathcal{C}(X)$. Then for $\epsilon > 0$, there exists $N \in \mathbb{N}$ such that if $m, n \geq N$, then

$$\|f_n - f_m\| = \sup |f_n - f_m| < \epsilon.$$

Thus for all $x \in X$, $|f_n(x) - f_m(x)| < \epsilon$ and thus $\{f_n\}$ is uniformly convergent to some $f(x)$. By the previous proposition, f is continuous. Then there exists $N \in \mathbb{N}$ such that if $n \geq N$, $|f_n - f(x)| < 1$ for all x , and thus $|f(x)| < 1 + |f_n(x)|$, so f is bounded. □

Some notation: If $E \subset \mathbb{R}$, we write $\mathcal{C}^k(E) = \{f : E \rightarrow \mathbb{C} \mid f, f', \dots, f^{(k)} \in \mathcal{C}(E)\}$. (Notice $\mathcal{C}^0(E) = \mathcal{C}(E)$.)

Theorem 3.14

Let α be nondecreasing on $[a, b] \subset \mathbb{R}$, $f_n \in \mathcal{R}(\alpha)$ for all n , and assume $f_n \rightarrow f$ uniformly. Then

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

Proof. TBD. □

3.1 I missed class

wip: need to catch up on the lecture I missed (1/13/2023)

Definition 3.15. Two notions of **boundedness**:

1. A sequence of functions $\{f_n\} \in \mathbb{C}(X)$ is said to be **pointwise bounded** if for all $x \in X$, there exists $C(x)$ such that $|f_n(x)| \leq C(x)$ for all x .
2. A sequence of functions $\{f_n\} \in \mathbb{C}(X)$ is said to be **uniformly bounded** if for all $x \in X$, there exists a constant M such that $|f_n(x)| \leq M$ for all x .

Definition 3.16. A family \mathcal{F} of complex functions f defined on a set E of a metric space X is said to be **equicontinuous** on E if for every $\epsilon > 0$, there exists a $\delta > 0$ such that

$$|f(x) - f(y)| < \epsilon$$

whenever $d(x, y) < \delta$, where $x, y \in E$, $f \in \mathcal{F}$.

Indeed, it is the case that uniform convergence of sequences of functions and this notion of equicontinuity are related to one another.

Theorem 3.17

If K is compact set, $f_n \in \mathcal{C}(K)$ and $f_n \rightarrow f$ uniformly on K for $n \in \mathbb{N}$, then $\{f_n\}_{n \in \mathbb{N}}$ is equicontinuous.

Proof. For $\epsilon > 0$, there exists an $N \in \mathbb{N}$ such that for any $x \in K$,

$$|f_n(x) - f(x)| < \frac{\epsilon}{3}$$

whenever $n \geq N$. Furthermore, since $f_n \rightarrow f$ uniformly, f is continuous; because K is compact, we even have f uniformly continuous. So there exists a $\delta' > 0$ such that if $d(x, y) < \delta'$, then

$$|f(x) - f(y)| < \frac{\epsilon}{3}.$$

So, if $d(x, y) < \delta'$ and $m, n \geq N$, we have

$$|f_n(x) - f_n(y)| \leq |f_n(x) - f(x)| + |f(x) - f(y)| + |f(y) - f_n(y)| < \epsilon.$$

Finally, f_1, \dots, f_N are continuous on a compact metric space, so they are uniformly continuous. Thus for each $1 \leq j \leq N$, there exists a $\delta_j > 0$ such that

$$|f_j(x) - f_j(y)| < \epsilon \quad (j = 1, \dots, N).$$

Set $\delta = \min(\delta', \delta_1, \dots, \delta_N)$, and we're done. □

Lemma 3.18

If K is compact, then there exists countable dense subset of K .

Proof. We can cover K with $\{B(x, \frac{1}{n}) \mid x \in K\}_{n \in \mathbb{N}}$. (Here, we shall abuse the notation $B(a, b)$ to represent the neighborhood of radius b centered at a , and x_j^n to represent the element x_j with corresponding neighborhood $B(x_j, \frac{1}{n})$.) For any $n \in \mathbb{N}$, there exists a finite subcover $\{B(x_j^n, \frac{1}{n})\}$ of balls of fixed radius $\frac{1}{n}$. Then for all $n \in \mathbb{N}$ and $y \in K$, there exists x_j^n such that $d(y, x_j^n) < \frac{1}{n}$. Take

$$S = \{x_j^n \mid n \in \mathbb{N}, j = 1, \dots, N\}.$$

□

Lemma 3.19

Given countable S and uniformly bounded sequence of functions f_n , there exists subsequence converging to every element of S

Proof. Let $S = \{x_1, \dots\}$. Since the sequence $f_n(x_1)$ is bounded in \mathbb{C} (i.e. $\sup |f_n| \leq M$ for all $n \in \mathbb{N}$), there exists a subsequence $f_{n_j^1}$ such that $f_{n_j^1}(x_1)$ converges. (Abusing more notation, let the sequence of subindices n_j^n only consist of the sequence of indices n_j^m if $m < n$.) Similarly, because $f_{n_j^1}(x_2) \leq M$ for all j , there exists a subsequence n_j^2 of n_j^1 such that $f_{n_j^2}(x_2)$ converges. Since $f_{n_j^2}$ is a subsequence of $f_{n_j^1}$, it also converges at x_1 . Then $f_{n_j^3}$ converges at x_3 (and thus at x_1 and x_2); by induction, it can be seen that $f_{n_j^k}$ converges at x_1, \dots, x_k . Now, to obtain an explicit subsequence, we shall **diagonalize** (recall Cantor's diagonalization argument from proving the countable union of countable sets is countable!), by setting

$$g_j = f_{n_j^j}.$$

For all k , if $j \geq k$, then $f_{n_j^j}$ is a subsequence of $f_{n_j^k}$, so $g_j(x_1), \dots, g_j(x_k)$ converge as $j \rightarrow \infty$. □

Theorem 3.20 (Arzelà–Ascoli)

K compact, $f_n \in \mathcal{C}(K)$ for $n = 1, 2, \dots$. Assume $\{f_n\}_{n \in \mathbb{N}}$ bounded in $\mathcal{C}(K)$ (i.e. uniformly bounded) and equicontinuous. Then there exists a convergent subsequence in $\mathcal{C}(K)$ (i.e. uniformly convergent).

Proof. Using Lemma 3.18, pick a countable and dense $S \subset K$. Using Lemma 3.19, pick a subsequence g_j of f_n converging on x for all $x \in S$. If we show g_j is uniformly convergent on K , then we're done:

We can do so by showing g_j is uniformly Cauchy. It follows from equicontinuity that for all $\epsilon > 0$, there exists $\delta > 0$ such that if $d(x, y) < \delta$, then for all j ,

$$|g_j(x) - g_j(y)| < \frac{\epsilon}{3}. \quad (4)$$

By Lemma 3.18, we can obtain, from the open cover $\{B(x_j, \delta) \mid x_j \in S\}$, a finite subcover $\{B(x, \delta) \mid x \in S_\delta\}$, where S_δ is finite. Now, since g_j converges to every element of S , there exists $N \in \mathbb{N}$ such that for all $x \in S_\delta$

$$|g_n(x) - g_m(x)| < \frac{\epsilon}{3} \quad (5)$$

whenever $m, n \geq N$. (Take $N = \max\{N_x \mid x \in S_\delta\}$.) Now, for all $i, j \geq N$, $y \in K$, there exists $x \in S_\delta$ such that $d(y, x) < \delta$, so (4) and (5) give

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

□

Remark 3.21. Rudin displays the Arzelà–Ascoli theorem with slightly weaker conditions: he requires $\{f_n\}$ to be a pointwise bounded sequence of complex functions on a countable set. However, pointwise boundedness is almost never used, so we'll choose not to think about it.

Remark 3.22. bounds on derivatives (or difference quotients) give equicontinuity. (MVT probably comes into play.....)

