

MATH 4318: Analysis II

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Lecture 1

Jan. 9 — The Derivative

1.1 Defining the Derivative

Definition 1.1. Let f be a real-valued function on an open interval $U \subseteq \mathbb{R}$. Let $x_0 \in U$, we say f is *differentiable* at x_0 if

$$\lim_{x \rightarrow x_0} \frac{f(x) - f(x_0)}{x - x_0} = \lim_{h \rightarrow 0} \frac{f(x_0 + h) - f(x_0)}{h}$$

exists. If it does, then this limit, denoted by $f'(x_0)$, is called the *derivative* of f at x_0 .

Remark. By definition, for any $\epsilon > 0$, there exists $\delta > 0$ such that

$$\left| \frac{f(x) - f(x_0)}{x - x_0} - f'(x_0) \right| \leq \epsilon$$

if $|x - x_0| < \delta$ and $x \in U$. Multiplying both sides by $|x - x_0|$ yields

$$|f(x) - f(x_0) - f'(x_0)(x - x_0)| \leq \epsilon|x - x_0|.$$

In other words,

$$|f(x) - \varphi(x)| \leq \epsilon|x - x_0|$$

where $\varphi(x) = f(x_0) + f'(x_0)(x - x_0)$. In other words, $\varphi(x)$ is a first-order approximation of $f(x)$ near x_0 . Geometrically, this is approximating the graph of $y = f(x)$ by the tangent line $y = \varphi(x)$.

1.2 Immediate Properties

Proposition 1.1. Let $U \subseteq \mathbb{R}$ be an open set and $f : U \rightarrow \mathbb{R}$. If f is differentiable at $x_0 \in U$, then f is continuous at x_0 .

Proof. Pick any $\epsilon_0 > 0$. Then there exists $\delta_0 > 0$ such that whenever $|x - x_0| < \delta_0$ and $x \in U$,

$$|f(x) - f(x_0) - f'(x_0)(x - x_0)| \leq \epsilon_0|x - x_0|.$$

By the triangle inequality,

$$|f(x) - f(x_0)| \leq \epsilon_0|x - x_0| + |f'(x_0)||x - x_0| = (\epsilon_0 + |f'(x_0)|)|x - x_0|.$$

Now for any $\epsilon > 0$, choose $\delta = \min\{\delta_0, \epsilon/(\epsilon_0 + |f'(x_0)|)\}$. Then

$$|f(x) - f(x_0)| \leq (\epsilon_0 + |f'(x_0)|)|x - x_0| < (\epsilon_0 + |f'(x_0)|)\delta \leq \epsilon$$

whenever $|x - x_0| < \delta$ and $x \in U$. Thus f is continuous at x_0 . □

Example 1.1.1. Take the function

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

Note that f is continuous on \mathbb{R} . For $x \neq 0$, continuity is clear since both x and $\sin(1/x)$ are continuous. At $x = 0$, we have

$$\lim_{x \rightarrow 0} f(x) = \lim_{x \rightarrow 0} x \sin(1/x) = 0 = f(0)$$

since $|x \sin(1/x)| \leq |x|$ for all $x \in \mathbb{R}$, so f is also continuous at $x = 0$. However, f is not differentiable at $x = 0$. Consider the limit

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

which does not exist since $\sin(1/x)$ oscillates. So f is not differentiable at $x = 0$.

Example 1.1.2. Take the function $f(x) = |x|$, which is continuous everywhere on \mathbb{R} . However, f is not differentiable at $x = 0$, since

$$\lim_{x \rightarrow 0} \frac{f(x) - f(0)}{x - 0} = \lim_{x \rightarrow 0} \frac{|x|}{x}.$$

Note that

$$\frac{|x|}{x} = \begin{cases} 1 & \text{if } x > 0 \\ -1 & \text{if } x < 0, \end{cases}$$

so the limit does not exist as $x \rightarrow 0$. Thus f is not differentiable at $x = 0$.

Remark. For the previous example, we can however define the *left (right) derivative* by

$$f'_-(x_0) = \lim_{x \rightarrow x_0^-} \frac{f(x) - f(x_0)}{x - x_0} \quad \text{and} \quad f'_+(x_0) = \lim_{x \rightarrow x_0^+} \frac{f(x) - f(x_0)}{x - x_0}.$$

If f is differentiable, then $f'_-(x_0) = f'_+(x_0)$. In the previous example, $f'_-(0) = -1$ and $f'_+(0) = 1$. For the first example however, even $f'_\pm(0)$ does not exist.

Remark. In one dimension, the existence of the derivative implies that the function is differentiable (the function is approximated by a linear function). However, in multiple dimensions, the existence of partial derivatives does not imply differentiability.

1.3 Rules for Differentiation

Proposition 1.2. Let $U \subseteq \mathbb{R}$ be open and $f, g : U \rightarrow \mathbb{R}$ be differentiable. Then

1. $(f + g)'(x_0) = f'(x_0) + g'(x_0)$
2. $(fg)'(x_0) = f'(x_0)g(x_0) + f(x_0)g'(x_0)$
3. if $g(x_0) \neq 0$, then $(f/g)'(x_0) = (f'(x_0)g(x_0) - f(x_0)g'(x_0))/(g(x_0)^2)$.

Proof. Find in textbook (Rosenlicht). □

Proposition 1.3. We have $\frac{d}{dx}(c) = 0$, $\frac{d}{dx}(x) = 1$, and $\frac{d}{dx}(x^n) = nx^{n-1}$ for all $n \in \mathbb{N}$.

Proof. We prove the last claim (the power rule) for $n \geq 1$ by induction. The base case $n = 1$ is the first claim which is true. Now suppose that the result holds for any $n \leq k \in \mathbb{N}$, and we show that it remains true for $n = k + 1$. By the product rule, we have

$$\frac{d}{dx}(x^{k+1}) = \frac{d}{dx}(x \cdot x^k) = \frac{d}{dx}(x) \cdot x^k + x \cdot \frac{d}{dx}(x^k) = x^k + xkx^{k-1} = (k+1)x^k.$$

Thus by induction this holds for all $n \geq 1$. We can do negative integers by the quotient rule. \square

Remark. The power rule actually holds for any $n \in \mathbb{R}$.

Proposition 1.4 (Chain rule). *Let U and V be open sets of \mathbb{R} and let $f : U \rightarrow V, g : V \rightarrow \mathbb{R}$ be differentiable. Let $x_0 \in U$ be such that $f'(x_0)$ and $g'(f(x_0))$ exist. Then $(g \circ f)'(x_0)$ exists and*

$$(g \circ f)'(x_0) = g'(f(x_0))f'(x_0).$$

Proof. For any fixed y_0 for which $g'(y_0)$ exists, set

$$A(y, y_0) = \begin{cases} (g(y) - g(y_0))/(y - y_0) & \text{if } y \in V \text{ and } y \neq y_0 \\ g'(y_0) & \text{if } y = y_0. \end{cases}$$

Then A is continuous at y_0 . To find $(g \circ f)'(x_0)$, observe that

$$\begin{aligned} \lim_{x \rightarrow x_0} \frac{g(f(x)) - g(f(x_0))}{x - x_0} &= \lim_{x \rightarrow x_0} \frac{A(f(x), f(x_0))(f(x) - f(x_0))}{x - x_0} \\ &= \lim_{x \rightarrow x_0} A(f(x), f(x_0)) \lim_{x \rightarrow x_0} \frac{f(x) - f(x_0)}{x - x_0} = g'(f(x_0))f'(x_0), \end{aligned}$$

by the continuity of A at $f(x_0)$ and the differentiability of f at x_0 . \square

Remark. The rough idea of what we did here is

$$\begin{aligned} \lim_{x \rightarrow x_0} \frac{g(f(x)) - g(f(x_0))}{x - x_0} &= \lim_{x \rightarrow x_0} \frac{g(f(x)) - g(f(x_0))}{f(x) - f(x_0)} \frac{f(x) - f(x_0)}{x - x_0} \\ &= \lim_{x \rightarrow x_0} \frac{g(f(x)) - g(f(x_0))}{f(x) - f(x_0)} \lim_{x \rightarrow x_0} \frac{f(x) - f(x_0)}{x - x_0} = g'(f(x_0))f'(x_0). \end{aligned}$$

But does not quite work as stated since it might be that $f(x) = f(x_0)$ even if $x \neq x_0$. We can fix this by introducing the function A as we did in the proof, though the overall idea is the same.

Remark. If f is monotone near x_0 , then we can define the *inverse function* f^{-1} so that $(f^{-1} \circ f)(x) = x$ near x_0 . If $f'(x_0)$ exists, then by the chain rule applied to $x = (f^{-1} \circ f)(x)$ at $x = x_0$ we have

$$1 = \frac{d}{dx}(f^{-1} \circ f)(x_0) = \frac{d}{dx}f^{-1}(f(x_0)) \cdot f'(x_0) \implies \frac{d}{dx}f^{-1}(f(x_0)) = \frac{1}{f'(x_0)}.$$

Example 1.1.3. Let $f(x) = e^x$ with $f^{-1}(x) = \ln(x)$. Since $f'(x) = f(x) = e^x$, we have

$$\frac{d}{dx}f^{-1}(f(x_0)) = \frac{1}{f'(x_0)} \implies \frac{d}{dx}\ln(e^{x_0}) = \frac{1}{e^{x_0}}.$$

Letting $e^{x_0} = h$, we have $\frac{d}{dx}\ln(x)|_{x=h} = 1/h$, which recovers the familiar formula.

Lecture 2

Jan. 11 — The Mean Value Theorem

2.1 The Mean Value Theorem

Lemma 2.1. *Let $I \subseteq \mathbb{R}$ be open, $f : I \rightarrow \mathbb{R}$ is differentiable at $x_0 \in I$ and $f'(x_0) \neq 0$. Suppose $f'(x_0) > 0$, then there exists $\delta > 0$ such that for any $x \in (x_0 - \delta, x_0 + \delta)$,*

1. *if $x > x_0$, then $f(x) > f(x_0)$,*
2. *if $x < x_0$, then $f(x) < f(x_0)$.*

Proof. Take $\epsilon = f'(x_0)/2$. By the definition of the derivative, there exists $\delta > 0$ such that for any $|x - x_0| < \delta$, we have

$$\left| \frac{f(x) - f(x_0)}{x - x_0} - f'(x_0) \right| < \epsilon = \frac{1}{2}f'(x_0).$$

By the triangle inequality,

$$\frac{f(x) - f(x_0)}{x - x_0} > \frac{1}{2}f'(x_0) > 0.$$

This quotient being positive immediately implies the desired results. \square

Theorem 2.1. *If $f(x)$ is differentiable in an open interval I and f obtains its local maximum (or minimum) at $x_0 \in I$, then $f'(x_0) = 0$.*

Proof. Suppose otherwise that $f'(x_0) \neq 0$. Assume without loss of generality that $f'(x_0) > 0$. Then by the previous lemma, there exists $\delta > 0$ such that for $x \in (x_0 - \delta, x_0 + \delta)$, if $x > x_0$ then $f(x) > f(x_0)$ and if $x < x_0$ then $f(x) < f(x_0)$. So x_0 cannot be a local maximum or minimum, which is a contradiction. \square

Theorem 2.2 (Rolle's middle value theorem). *Let $f(x)$ be continuous on $[a, b]$ and differentiable in (a, b) . Suppose $f(a) = f(b)$, then there exists $x_0 \in (a, b)$ such that $f'(x_0) = 0$.*

Proof. Since f is continuous on a compact set, it obtains both a maximum and minimum on $[a, b]$. Let M be the maximum and m be the minimum. If $M = m$, then $f(x) \equiv M$ and $f'(x) = 0$ everywhere. If $M > m$, then at least one of the maximum or minimum must be obtained at an interior point $x_0 \in (a, b)$ since $f(a) = f(b)$. By the previous theorem, $f'(x_0) = 0$ at this point and we are done. \square

Example 2.0.1. Show that the equation $4ax^3 + 3bx^2 + 2cx = a + b + c$ has at least one root in $(0, 1)$.

Proof. Consider the equation

$$4ax^3 + 3bx^2 + 2cx - (a + b + c) = 0.$$

Notice that the left hand side is the derivative of the function

$$f(x) = ax^4 + bx^3 + cx^2 - (a + b + c)x.$$

So we just need to show that $f'(x) = 0$ for some x . For this, we can check that $f(0) = f(1) = 0$, and thus by Rolle's theorem there exists $x_0 \in (0, 1)$ such that $f'(x_0) = 0$. So x_0 is a root. \square

Theorem 2.3 (Lagrange's middle value theorem). *Let $f(x)$ be continuous on $[a, b]$ and differentiable in (a, b) . Then there exists $x_0 \in (a, b)$ such that*

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

Proof. Subtract the secant line through $(a, f(a))$ and $(b, f(b))$ from $f(x)$ to get

$$g(x) = f(x) - \frac{f(b) - f(a)}{b - a}(x - a).$$

Note that $g(a) = g(b) = f(a)$. So by Rolle's theorem, there exists $x_0 \in (a, b)$ such that $g'(x_0) = 0$. But

$$0 = g'(x_0) = f'(x_0) - \frac{f(b) - f(a)}{b - a},$$

which is the desired result. \square

Corollary 2.3.1. *Suppose $f \in C([a, b])$, i.e. f is continuous on $[a, b]$, and that f is differentiable in (a, b) . Then the following statements are equivalent:*

1. $f'(x) \geq 0$ in (a, b) ,
2. $f(x)$ is increasing, i.e. if $x_1 > x_2$, then $f(x_1) \geq f(x_2)$.

In particular, if $f'(x) > 0$ in (a, b) , then $f(x)$ is strictly increasing, i.e. if $x_1 > x_2$, then $f(x_1) > f(x_2)$.

Proof. $(2 \Rightarrow 1)$ For any $x_0 \in (a, b)$,

$$f'(x_0) = \lim_{h \rightarrow 0} \frac{f(x_0 + h) - f(x_0)}{h} \geq 0$$

since $f(x_0 + h) - f(x_0) \geq 0$ for $h > 0$ as f is increasing.

$(1 \Rightarrow 2)$ Take $x_1 > x_2$, then by Lagrange's theorem there exists $\xi \in (x_2, x_1)$ such that

$$f(x_2) - f(x_1) = f'(\xi)(x_2 - x_1) \geq 0.$$

So $f(x_1) \geq f(x_2)$. The strict version follows from changing the above inequality to a strict one. \square

2.2 Applications

Example 2.0.2. Show that

$$\frac{2}{2x+1} < \ln(1 + 1/x)$$

for any $x > 0$.

Proof. Let $f(x) = 2/(2x+1) - \ln(1 + 1/x)$. Taking the derivative yields

$$f'(x) = \frac{1}{(2x+1)^2 x(x+1)} > 0,$$

so f is strictly increasing in $(0, \infty)$. Note that $f \rightarrow 0$ as $x \rightarrow \infty$, so $f(x) < 0$ for all $x > 0$. □

Example 2.0.3. Show that $b/a > b^a/a^b$ when $b > a > 1$.

Proof. Take log on both sides to get $\ln b - \ln a > a \ln b - b \ln a$. This gives

$$(b-1) \ln a > (a-1) \ln b \iff \frac{\ln a}{a-1} > \frac{\ln b}{b-1}.$$

Note that this is a monotonicity property. So let $f(x) = (\ln x)/(x-1)$ for $x > 1$. Then

$$f'(x) = \frac{x-1-x \ln x}{x(x-1)^2} < 0$$

when $x > 1$ because $x-1-x \ln x < 0$. To see the last claim, define $g(x) = x-1-x \ln x$ and note that $g'(x) = -\ln x < 0$ for $x > 1$. But $g(0) = 0$, so $g(x) < 0$ for $x > 1$. So f is strictly decreasing. □

Example 2.0.4. Show that

$$\lim_{x \rightarrow 0} \frac{e^x - e^{\sin x}}{x - \sin x} = 1.$$

Proof. Let $f(x) = e^x$. Then there exists ξ between x and $\sin x$ such that

$$e^x - e^{\sin x} = (x - \sin x)e^{\xi(x)},$$

where the choice of ξ may vary for different x . Then

$$\lim_{x \rightarrow 0} \frac{e^x - e^{\sin x}}{x - \sin x} = \lim_{x \rightarrow 0} e^{\xi(x)}.$$

Now note that $\xi(x)$ is always between x and $\sin x$, which both tend to 0 as $x \rightarrow 0$. So by the squeeze theorem we have $\xi(x) \rightarrow 0$ as $x \rightarrow 0$ and thus $e^{\xi(x)} \rightarrow 1$ as $x \rightarrow 0$. □

2.3 Cauchy's Mean Value Theorem

Theorem 2.4 (Cauchy's middle value theorem). *Let $f, g \in C([a, b])$ and f, g be differentiable in (a, b) . Suppose $g'(x) \neq 0$ for any $x \in (a, b)$. Then there exists $x_0 \in (a, b)$ such that*

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

Proof. Use a similar construction as before and let

$$F(x) = f(x) - f(a) - \frac{f(b) - f(a)}{g(b) - g(a)}(g(x) - g(a)).$$

Note that $F(b) = F(a) = 0$, so by Rolle's theorem there exists $x_0 \in (a, b)$ such that $F'(x_0) = 0$. Then

$$0 = F'(x_0) = f'(x_0) - \frac{f(b) - f(a)}{g(b) - g(a)}g'(x_0),$$

which implies the desired result. □

Remark. The $g'(x) \neq 0$ condition guarantees that g is monotone, even if g' may fail to be continuous.

Remark. If g is a monotonically increasing function, we can view g as a mapping $g : [a, b] \rightarrow [g(a), g(b)]$, which we can view as a change of variables $x \mapsto u$. Since g is monotone, we have an inverse $u = g^{-1}(x)$. Then

$$f(x) = f(g^{-1}(u)) = (f \circ g^{-1})(u) = \tilde{f}(u).$$

By Lagrange's theorem,

$$\frac{\tilde{f}(g(b)) - \tilde{f}(g(a))}{g(b) - g(a)} = \tilde{f}'(u_0)$$

for some $u_0 \in (g(a), g(b))$. Now note that

$$\tilde{f}(g(b)) = (f \circ g^{-1})(g(b)) = f(b), \quad \tilde{f}(g(a)) = f(a).$$

So the left-hand side is precisely

$$\text{LHS} = \frac{f(b) - f(a)}{g(b) - g(a)}.$$

By the chain rule, we have

$$\text{RHS} = \tilde{f}'(u_0) = (f \circ g^{-1})'(u_0) = f'(g^{-1}(u_0))(g^{-1})'(u_0) = f'(x_0) \frac{1}{g'(x_0)}.$$

This recovers Cauchy's mean value theorem. So they are equivalent even if Cauchy's seems stronger.

Lecture 3

Jan. 16 — Taylor's Theorem

3.1 Darboux's Lemma

Lemma 3.1 (Darboux's lemma). *If f is differentiable in (a, b) , continuous on $[a, b]$ and $f'(a) < f'(b)$, then for any $c \in (f'(a), f'(b))$, there exists $x_0 \in (a, b)$ such that $f'(x_0) = c$.*

Proof. See homework. □

Remark. There exists an example of a differentiable function $f(x)$ but $f'(x)$ is not continuous, e.g.

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

We can compute that

$$f'(x) = \begin{cases} 2x \sin(1/x) - \cos(1/x) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0, \end{cases}$$

and we can verify as an exercise that $f'(x)$ is not continuous at $x = 0$.

Remark. Darboux's lemma guarantees that $g'(x) \neq 0$ implies either $g'(x) > 0$ or $g'(x) < 0$ everywhere in the conditions for Cauchy's mean value theorem.

3.2 L'Hôpital's Rule

Theorem 3.1 (L'Hôpital's rule, $0/0$). *Let f, g be differentiable in (a, b) , $\lim_{x \rightarrow a^+} f(x) = \lim_{x \rightarrow a^+} g(x) = 0$, and $g'(x) \neq 0$ for any $x \in (a, b)$. Then if $\lim_{x \rightarrow a^+} f'(x)/g'(x)$ exists, we have*

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

Proof. By Cauchy's theorem, for any $x \in (a, b)$, there exists $\xi(x) \in (a, x)$ such that

$$\frac{f(x)}{g(x)} = \frac{f(x) - f(a)}{g(x) - g(a)} = \frac{f'(\xi(x))}{g'(\xi(x))}.$$

If $x \rightarrow a^+$, then $\xi(x) \rightarrow a^+$, so

$$\lim_{x \rightarrow a^+} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a^+} \frac{f'(\xi(x))}{g'(\xi(x))} = \lim_{x \rightarrow a^+} \frac{f'(x)}{g'(x)},$$

as desired. □

Corollary 3.1.1. *Let f, g be differentiable in (a, ∞) , $\lim_{x \rightarrow \infty} f(x) = \lim_{x \rightarrow \infty} g(x) = 0$, and $g'(x) \neq 0$ for any $x \in (a, \infty)$. Then if $\lim_{x \rightarrow \infty} f'(x)/g'(x)$ exists, we have*

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

Proof. Assume $a > 0$. Define $\tilde{f}(y) = f(1/y)$ and $\tilde{g}(y) = g(1/y)$ with $y \in (0, 1/a)$. By L'Hôpital's rule,

$$\lim_{y \rightarrow 0^+} \frac{\tilde{f}(y)}{\tilde{g}(y)} = \lim_{y \rightarrow 0^+} \frac{\tilde{f}'(y)}{\tilde{g}'(y)} = \lim_{y \rightarrow \infty} \frac{f'(1/y) \cdot (-1/y^2)}{g'(1/y) \cdot (-1/y^2)} = \lim_{x \rightarrow \infty} \frac{f'(x)}{g'(x)},$$

as desired. □

Theorem 3.2 (L'Hôpital, ∞/∞). *Let f, g be differentiable in (a, b) , $\lim_{x \rightarrow a^+} |f(x)| = \lim_{x \rightarrow a^+} |g(x)| = \infty$, and $g'(x) \neq 0$ for any $x \in (a, b)$. Then if $\lim_{x \rightarrow a^+} f'(x)/g'(x)$ exists, we have*

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

Proof. Left as an exercise. □

Remark. Saying that the absolute values of f and g go to infinity works, since the existence of the limit rules out oscillatory behavior.

Remark. These cases of ∞/∞ and $0/0$ are called *indefinite types*. Other indefinite types include $0 \cdot \infty$, 0^0 , ∞^0 , 1^∞ , $\infty - \infty$, etc. But we can try to reduce them to the cases we know. For example, if $f(x) \rightarrow 0^+$ and $g(x) \rightarrow 0^+$ when $x \rightarrow x_0$, then $\lim_{x \rightarrow x_0} f(x)^{g(x)}$ is 0^0 . Letting $y(x) = f(x)^{g(x)}$, we can take the log to get

$$\ln y(x) = g(x) \ln f(x) = \frac{\ln f(x)}{1/g(x)} = \frac{\infty}{\infty}.$$

Example 3.0.1. We can see that (this is a $\infty - \infty$ case)

$$\lim_{x \rightarrow 0^+} \frac{1}{x^2} - \frac{\cot x}{x} = \lim_{x \rightarrow 0^+} \frac{1 + x \cot x}{x^2} = \lim_{x \rightarrow 0^+} \frac{-(\cot x - x \csc^2 x)}{2x \sin^2 x}.$$

Note that $x \cot x = x \cos x / \sin x \rightarrow 1$ as $x \rightarrow 0$. Now note that $\sin x / x \rightarrow 1$ as $x \rightarrow 0$, so we continue with

$$\lim_{x \rightarrow 0^+} \frac{-(\cot x - x \csc^2 x)}{2x \sin^2 x} = \lim_{x \rightarrow 0^+} \frac{x - \sin x \cos x}{2x^3} \frac{x^2}{\sin^2 x}$$

Since $x^2 / \sin^2 x \rightarrow 1$ as $x \rightarrow 0$, we can look at the remaining part to get

$$\lim_{x \rightarrow 0^+} \frac{x - \sin x \cos x}{2x^3} = \lim_{x \rightarrow 0^+} \frac{1 - \cos 2x}{6x^2} = \lim_{x \rightarrow 0^+} \frac{2 \sin 2x}{12x} = \frac{1}{3}.$$

So $\lim_{x \rightarrow 0^+} (1/x^2 - \cot x/x) = 1/3$.

3.3 Taylor's Theorem

Theorem 3.3 (Peano remainder term). *Let $f : [a, b] \rightarrow \mathbb{R}$ be differentiable at $x = a$ up to n th order of derivatives, i.e. $f'(a), f''(a), \dots, f^{(n)}(a)$ exist. Then as $x \rightarrow a^+$, we have*

$$f(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + o((x-a)^n).$$

Call the polynomial part of the above $P_n(x)$, which is also known as the Taylor polynomial of order n .

Proof. To show that the error term is $o((x-a)^n)$, we have

$$\lim_{x \rightarrow a^+} \frac{f(x) - P_n(x)}{(x-a)^n} = \lim_{x \rightarrow a^+} \frac{f'(x) - P'_n(x)}{n(x-a)^{n-1}} = \frac{1}{n!} \lim_{x \rightarrow a^+} \left[\frac{f^{n-1}(x) - f^{n-1}(a)}{x-a} - f^{(n)}(a) \right] = 0$$

by L'Hôpital's rule, where we used the observation that $f^{(k)}(a) = P_n^{(k)}(a)$ for $1 \leq k \leq n$. The final step is a result of the existence of $f^{(n)}(a)$. \square

Lemma 3.2 (Rolle's theorem for higher order derivatives). *Let $f \in C^n([a, b])$ and differentiable to $(n+1)$ order. If $f'(a) = \dots = f^{(n)}(a) = 0$ and $f(a) = f(b)$, then there exists $x_0 \in (a, b)$ such that $f^{(n+1)}(x_0) = 0$.*

Proof. Since $f(a) = f(b)$, by the usual Rolle's theorem there exists $x_1 \in (a, b)$ such that $f'(x_1) = 0$. Then since $f'(a) = f'(x_1) = 0$, by Rolle's theorem again, there exists $x_2 \in (a, x_1)$ such that $f''(x_2) = 0$. Repeat this to get $x_{n+1} \in (a, x_n) \subseteq (a, b)$ such that $f^{(n+1)}(x_{n+1}) = 0$. Take $x_0 = x_{n+1}$ to finish. \square

Theorem 3.4 (Lagrange remainder term). *Let $f \in C^n([a, b])$, in particular, $f'(a), \dots, f^{(n)}(a)$ exist. Additionally, assume f is $(n+1)$ -th differentiable in (a, b) .¹ Then*

$$f(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + R_n(x) \quad \text{where} \quad R_n(x) = \frac{f^{(n+1)}(\xi)}{(n+1)!} (x-a)^{n+1}$$

for some $\xi \in [a, x]$.

Proof. Define $P(x) = P_n(x) + \lambda(x-a)^{n+1}$, where we choose $\lambda \in \mathbb{R}$ such that $P(b) = f(b)$, i.e.

$$\lambda = \frac{f(b) - P_n(b)}{(b-a)^{n+1}}.$$

Consider $g(x) = f(x) - P(x)$, which satisfies $g(a) = g(b) = 0$ and $g'(a) = \dots = g^{(n)}(a) = 0$. Then by Rolle's theorem (higher order), there exists $\xi \in (a, b)$ such that $g^{(n+1)}(\xi) = 0$. In other words,

$$f^{(n+1)}(\xi) - P^{(n+1)}(\xi) = 0 \implies f^{(n+1)}(\xi) - \underbrace{(n+1)! \frac{f(b) - P_n(b)}{(b-a)^{n+1}}}_{\lambda} = 0.$$

This implies that

$$f(b) = P_n(b) + \frac{1}{(n+1)!} f^{(n+1)}(\xi) (b-a)^{n+1},$$

and since we picked b arbitrarily (kind of), we can take $b = x$ and we are done since $\xi \in [a, b]$. \square

¹Note that the $(n+1)$ -th derivative need not be continuous here.

Remark. The choice of ξ in Lagrange's remainder term may (and likely does) vary for different x .

Remark. The Taylor polynomial is unique in the sense that if $f : [a, b] \rightarrow \mathbb{R}$ and $f'(a), \dots, f^{(n)}(a)$ exist, then if

$$f(x) = p(x) + o((x - a)^n)$$

as $x \rightarrow a^+$ for some polynomial $p(x)$ with $\deg p \leq n$, then $p(x) = P_n(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x - a)^k$. This is because if $Q(x) = p(x) - P_n(x)$, then by Taylor's formula (Peano form), we get

$$\lim_{x \rightarrow a^+} \frac{Q(x)}{(x - a)^n} = \lim_{x \rightarrow a^+} \frac{p(x) - \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x - a)^k}{(x - a)^n} = 0.$$

From here this implies that $Q(x) = 0$ since $\deg Q \leq n$. Another way to see this is to plug in $x = a$, which deletes everything except the constant, and then ignore the constant and divide by $(x - a)$ to repeat.

Lecture 4

Jan. 18 — Taylor Polynomials

4.1 Common Taylor Polynomials

We have

$$\begin{aligned}e^x &= 1 + x + \frac{x^2}{2!} + \cdots + \frac{x^n}{n!} + o(x^n), \\ \sin x &= x - \frac{x^3}{3!} + \frac{x^5}{5!} - \cdots + \frac{(-1)^{n-1}x^{2n-1}}{(2n-1)!} + o(x^{2n}), \\ \cos x &= 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \cdots + \frac{(-1)^n x^{2n}}{(2n)!} + o(x^{2n+1}), \\ (1+x)^\alpha &= 1 + \alpha x + \frac{\alpha(\alpha-1)}{2!}x^2 + \cdots + \frac{\alpha(\alpha-1)\cdots(\alpha-n+1)}{n!}x^n + o(x^n), \\ \ln(1+x) &= x - \frac{x^2}{2} + \frac{x^3}{3} - \cdots + (-1)^{n-1}\frac{x^n}{n} + o(x^n).\end{aligned}$$

4.2 Combining Taylor Polynomials

Remark. If $a = 0$ and $f(x)$ is even in $(-b, b)$, then

$$f(x) = \sum_{k=0}^{n/2} a_k x^{2k} + o(x^n).$$

Similarly if $f(x)$ is odd in $(-b, b)$, then

$$f(x) = \sum_{k=0}^{n/2} a_k x^{2k+1} + o(x^{n+1}).$$

Remark. To create new Taylor polynomials from known ones, we can observe that if $f(x) = P_n(x) + o((x-a)^n)$ and $g(x) = Q_n(x) + o((x-a)^n)$, then

$$f(x) + g(x) = (P_n(x) + Q_n(x)) + o((x-a)^n) \quad \text{and} \quad f(x)g(x) = \underbrace{(P_n(x)Q_n(x))}_{\text{take first } n \text{ terms}} + o((x-a)^n).$$

If $P_n(x) = \sum_{k=0}^n a_k(x-a)^k$ and $Q_n(x) = \sum_{k=0}^n b_k(x-a)^k$, then $f(x)g(x)$ has Taylor polynomial $\sum_{k=0}^n c_k(x-a)^k$ where

$$c_k = \sum_{i=0}^k a_i b_{k-i}.$$

If $h(x) = f(x)/g(x)$ and $g(x) \neq 0$ near $x = a$, then $f(x) = h(x)g(x)$. Let $h(x) = \sum_{k=0}^n c_k(x-a)^k + o((x-a)^n)$, then

$$a_k = \sum_{i=0}^k c_i b_{k-i}$$

for $0 \leq k \leq n$, after which we can solve for the c_k .

Example 4.0.1. Find the Taylor polynomial for $\tan x$ up to $n = 5$.

Proof. Note that $\tan x$ is odd, so we can write

$$\tan x = x + a_3 x^3 + a_5 x^5 + o(x^5).$$

Now since $\tan x = \sin x / \cos x$, we have $\sin x = \tan x \cos x$, so

$$x - \frac{x^3}{6} + \frac{x^5}{5!} + o(x^5) = (x + a_3 x^3 + a_5 x^5) \left(1 - \frac{x^2}{2!} + \frac{x^4}{4!}\right)$$

We can solve to get

$$\begin{cases} -\frac{1}{6} = -\frac{1}{2} + a_3 \\ \frac{1}{5!} = \frac{1}{4!} - \frac{a_3}{2!} + a_5 \end{cases} \implies a_3 = -\frac{1}{3}, \quad a_5 = \frac{2}{15}$$

as the coefficients for the Taylor polynomial. □

Remark. If

$$f'(x) = \sum_{k=0}^n b_k (x-a)^k + o((x-a)^n),$$

then the anti-derivative of $f(x)$ has

$$f(x) = f(x_0) + \sum_{k=0}^n a_{k+1} (x-a)^{k+1} + o((x-a)^{n+1}),$$

where $a_{k+1} = b_k / (k+1)$ for $0 \leq k \leq n$. This is because

$$b_k = \frac{(f')^{(k)}(a)}{k!} = \frac{f^{(k+1)}(a)}{k!} \quad \text{and} \quad a_{k+1} = \frac{f^{(k+1)}(a)}{k+1} = \frac{1}{k+1} \frac{f^{(k+1)}(a)}{k!} = \frac{b_k}{k+1}.$$

Example 4.0.2. Find the Taylor polynomial for $f(x) = \arctan x$.

Proof. Recall that

$$f'(x) = \frac{1}{1+x^2} = \sum_{k=0}^n (-1)^k x^{2k}.$$

Using the above we get

$$f(x) = \arctan x = \sum_{k=0}^n (-1)^k \frac{x^{2k+1}}{2k+1} + o(x^{2n+2})$$

as the Taylor polynomial. □

4.3 Applications for Taylor Polynomials

4.3.1 Finding Limits

Remark. Let $f(x) = ax^n + o(x^n)$ as $x \rightarrow 0$ and $g(x) = bx^n + o(x^n)$ where $b \neq 0$. Then

$$\lim_{x \rightarrow 0} \frac{f(x)}{g(x)} = \frac{a}{b}.$$

Remark. For the polynomial of $f(g(x))$, we can do

$$f(u) = \sum_{k=0}^n a_k(u - g(a))^k + o((u - g(a))^n), \quad \text{where} \quad u = g(x) = \sum_{k=0}^n b_k(x - a)^k + o((x - a)^n).$$

Then we can substitute in $u = g(x)$ to find the overall polynomial.

Example 4.0.3. Find

$$\lim_{x \rightarrow 0} \frac{\sqrt{1 + 2 \tan x} - e^x + x^2}{\arcsin x - \sin x}.$$

Proof. Note that

$$\begin{aligned} \sqrt{1 + 2 \tan x} - e^x + x^2 &= \frac{2x^3}{3} + o(x^3), \\ \arcsin x - \sin x &= \frac{x^3}{3} + o(x^3). \end{aligned}$$

So the desired limit is 2. □

Remark. If $f(x) = ax^n + o(x^n)$ and $g(x) = bx^m + o(x^m)$ for $a, b \neq 0$, then

$$\lim_{x \rightarrow 0} \frac{f(x)}{g(x)} = \begin{cases} a/b & \text{if } m = n, \\ 0 & \text{if } m < n, \\ \infty & \text{if } m > n. \end{cases}$$

Example 4.0.4. Assume $f(x) = 1 + ax^n + o(x^n)$ where $a \neq 0$ and

$$g(x) = \frac{1}{bx^n + o(x^n)}, \quad \text{i.e.} \quad \frac{1}{g(x)} = bx^n + o(x^n).$$

for $b \neq 0$. Then

$$\lim_{x \rightarrow 0} f(x)^{g(x)} = e^{a/b}.$$

Let $y(x) = f(x)^{g(x)}$, then $\ln y(x) = g(x) \ln f(x)$. Note that

$$\ln f(x) = \ln(1 + ax^n + o(x^n)) = ax^n + o(x^n),$$

so that

$$\frac{\ln f(x)}{1/g(x)} = \frac{ax^n + o(x^n)}{bx^n + o(x^n)} \rightarrow \frac{a}{b}$$

as $x \rightarrow 0$. Thus $\ln y(x) \rightarrow a/b$ and $y(x) \rightarrow e^{a/b}$ as $x \rightarrow 0$.

Example 4.0.5. Find

$$\lim_{x \rightarrow 0} [\cos(xe^x) - \ln(1-x) - x]^{\cot x^3}.$$

Proof. Here we have

$$f(x) = \cos(xe^x) - \ln(1-x) - x = 1 - \frac{2}{3}x^3 + o(x^3) \quad \text{and} \quad \frac{1}{g(x)} = \tan x^3 = x^3 + o(x^3).$$

Thus the limit is $e^{-2/3}$. □

4.3.2 Estimation

Example 4.0.6. Let $f(x)$ be twice differentiable in $[0, 1]$ and $f(0) = f(1)$. Further assume $|f''(x)| \leq M$ for $0 \leq x \leq 1$. Prove that $|f'(x)| \leq M/2$ for $0 \leq x \leq 1$.

Proof. Recall that Lagrange's form of Taylor's theorem says

$$f(x) = f(a) + f'(a)(x-a) + \frac{f''(\xi)}{2!}(x-a)^2$$

for some ξ between a and x . Thus for any $x \in (0, 1)$, we have

$$f(1) = f(x) + f'(x)(1-x) + \frac{f''(\xi_1)}{2}(1-x)^2.$$

Similarly, we have

$$f(0) = f(x) + f'(x)(-x) + \frac{f''(\xi_2)}{2}x^2.$$

Here $x \leq \xi_1 \leq 1$ and $0 \leq \xi_2 \leq x$. Since $f(1) = f(0)$, we can solve for $f'(x)$ to get

$$f'(x) = \frac{f''(\xi_2)x^2 - f''(\xi_1)(1-x)^2}{2}.$$

Then taking absolute values yields

$$|f'(x)| \leq M \left(\frac{x^2 + (1-x)^2}{2} \right) \leq \frac{M}{2} \max_{0 \leq x \leq 1} [x^2 + (1-x)^2] = \frac{M}{2},$$

as desired. □

Example 4.0.7. Let $f(x)$ be twice differentiable in $[0, 1]$ and $f'(a) = f'(b) = 0$. Then there exists $\xi \in (a, b)$ such that

$$|f''(\xi)| \geq 4 \frac{|f(a) - f(b)|}{(b-a)^2}.$$

Proof. Note that this is equivalent to

$$|f(b) - f(a)| \leq f''(\xi) \left(\frac{b-a}{2} \right)^2.$$

Then we have

$$f\left(\frac{b+a}{2}\right) = f(a) + \frac{f''(\xi_1)}{2} \left(\frac{b-a}{2}\right)^2 = f(b) - \frac{f''(\xi_2)}{2} \left(\frac{b-a}{2}\right)^2,$$

so that

$$f(b) - f(a) = \frac{f''(\xi_2) + f''(\xi_1)}{2} \left(\frac{b-a}{2} \right)^2.$$

From here we have

$$|f(b) - f(a)| \leq \underbrace{\frac{|f''(\xi_1)| + |f''(\xi_2)|}{2}}_{=|f''(\xi)|} \left(\frac{b-a}{2} \right)^2$$

for some $\xi \in (a, b)$ by Darboux's lemma, as desired.

□

Lecture 5

Jan. 23 — The Riemann Integral

5.1 The Anti-Derivative

Recall the *anti-derivative* from calculus:

Definition 5.1. Let $f : U \rightarrow \mathbb{R}$ where U is an interval in \mathbb{R} . If there exists a differentiable function $F : U \rightarrow \mathbb{R}$ such that $F'(x) = f(x)$ for all $x \in U$, then $F(x)$ is an *anti-derivative* of f , denoted

$$F(x) = \int f(x) dx.$$

This is also called the *indefinite integral* of f .

Remark. The anti-derivatives of a function can differ by a constant.

Example 5.1.1. Find an anti-derivative of $f(x) = |x|$ for $x \in \mathbb{R}$.

Proof. If $x > 0$, we have $f(x) = x$ and so $F(x) = x^2/2$. If $x < 0$, then $f(x) = -x$ and so $F(x) = -x^2/2$. We can also write this as

$$F(x) = x \cdot \frac{|x|}{2}.$$

Clearly for $x \neq 0$, we have $F'(x) = f(x)$. At $x = 0$, we have

$$\lim_{x \rightarrow 0} \frac{F(x) - f(0)}{x} = \lim_{x \rightarrow 0} \frac{1}{2}|x| = 0,$$

so $F'(0) = f(0)$ and F is an anti-derivative of f . □

Remark. The eventual goal is to show that any continuous function $f : [a, b] \rightarrow \mathbb{R}$ has an anti-derivative.

Example 5.1.2. Find an anti-derivative for

$$f(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x \leq 0 \\ -1 & \text{if } x < 0. \end{cases}$$

Proof. We can try to use $F(x) = |x|$, but recall that F is not differentiable at $x = 0$. More generally, suppose that $f(x)$ has some anti-derivative $F(x)$, i.e. $f(x) = F'(x)$. By Darboux's theorem, $f(x)$ must take all values in $(-1, 1)$, which is a contradiction with the definition of f . □

Remark. If $f(x)$ has a jump discontinuity, then it has no anti-derivative.

5.2 The Riemann Integral

Recall from calculus that if $f(x)$ is defined in $[a, b]$ and $F'(x) = f(x)$, then we have¹

$$\int_a^b f(x) dx = F(x) \Big|_a^b = F(b) - F(a).$$

We called this the *definite integral* of f in calculus, but we would like a more rigorous definition.

Definition 5.2. Let $a, b \in \mathbb{R}$ and $a < b$. A *partition* of the interval $[a, b]$ is a finite sequence of numbers x_0, x_1, \dots, x_n such that $a = x_0 < x_1 < \dots < x_n = b$.

Definition 5.3. The *width* of a partition x_0, x_1, \dots, x_n is $\max\{x_i - x_{i-1} : i = 1, 2, \dots, n\}$.

Definition 5.4. For any partition x_0, x_1, \dots, x_n , define the *Riemann sum* to be

$$S = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}),$$

where x'_i is any point between x_{i-1} and x_i , inclusive.²

Definition 5.5. Let $a, b \in \mathbb{R}$ with $a < b$ and $f : [a, b] \rightarrow \mathbb{R}$. We say f is *Riemann integrable* on $[a, b]$ if there exists $A \in \mathbb{R}$ such that for all $\epsilon > 0$, there exists $\delta > 0$ such that $|S - A| < \epsilon$ whenever S is any Riemann sum for a partition of $[a, b]$ with width less than δ . We call A the *Riemann integral* of f on $[a, b]$ and denote it by

$$A = \int_a^b f(x) dx.$$

Remark. If f is Riemann integrable, then

$$A = \int_a^b f(x) dx$$

is unique. This is because if A and A' are two numbers for the Riemann integral, then for any $\epsilon > 0$, there exists $\delta > 0$ such that

$$|A - S| < \epsilon \quad \text{and} \quad |A' - S| < \epsilon$$

for any Riemann sum S associated with a partition of width less than δ . Then

$$|A - A'| \leq |A - S| + |A' - S| < 2\epsilon,$$

so $A = A'$ and thus the Riemann integral is unique.

Example 5.5.1. Let $f(x) = c$ on $[a, b]$, a constant function. Then for any partition x_0, x_1, \dots, x_n ,

$$S = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}) = \sum_{i=1}^n c(x_i - x_{i-1}) = c(b - a) \implies \int_a^b c dx = c(b - a).$$

¹This is the *fundamental theorem of calculus*.

²The geometric intuition of the Riemann sum is an approximation for the *area* under the graph of f by rectangles.

Example 5.5.2. Fix $\xi \in [a, b]$ and let $f : [a, b] \rightarrow \mathbb{R}$ be defined by

$$f(x) = \begin{cases} 0 & \text{if } x \neq \xi \\ c & \text{if } x = \xi. \end{cases}$$

Check that

$$A = \int_a^b f(x) dx = 0.$$

Proof. For any partition $a = x_0 < x_1 < \cdots < x_n = b$ with width δ , we have

$$|S| = \left| \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}) \right| \leq |c|2\delta$$

since ξ can be in at most two of the intervals of the partition. Then for any $\epsilon > 0$, choose $\delta = \epsilon/(2|c|)$, so that $|S| < \epsilon$ for any partition of width less than δ . From this we can conclude that $A = 0$. \square

Example 5.5.3. Consider a step function. Let $\alpha, \beta \in [a, b]$ with $\alpha < \beta$. Define $f : [a, b] \rightarrow \mathbb{R}$ by

$$f(x) = \begin{cases} 1 & \text{if } x \in (\alpha, \beta) \\ 0 & \text{if } x \notin (\alpha, \beta) \text{ and } x \in [a, b]. \end{cases}$$

Note that f has no anti-derivative, but it is Riemann integrable. In fact,

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

To see this, take any partition $a = x_0 < x_1 < \cdots < x_n = b$ with width less than δ . Then

$$S = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}) = \sum_{[x_{i-1}, x_i] \cap [\alpha, \beta] \neq \emptyset} f(x'_i)(x_i - x_{i-1}).$$

Each partition is in two classes: Either (1) it only partially intersects $[\alpha, \beta]$ or (2) it is contained in $[\alpha, \beta]$. So

$$S = \underbrace{1(\text{total length of intervals of class 2})}_{I_1} + \underbrace{|f(x'_i)|(\text{total length of intervals of class 1})}_{I_2}.$$

We have $|I_1 - (\beta - \alpha)| < 2\delta$ and $|I_2| < 2\delta$ since there are at most two intervals of class 1. So

$$|S - (\beta - \alpha)| \leq |I_1| + |I_2| < 4\delta.$$

So $f(x)$ is Riemann integrable and

$$\int_a^b f(x) dx = \beta - \alpha,$$

as desired.

Example 5.5.4. Define $f : [a, b] \rightarrow \mathbb{R}$ by

$$f(x) = \begin{cases} 1 & \text{if } x \text{ is rational} \\ 0 & \text{if } x \text{ is irrational.} \end{cases}$$

Then $f(x)$ is not Riemann integrable. For any partition $a = x_0 < x_1 < \cdots < x_n = b$,

$$S = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}) = \begin{cases} b - a & \text{if } x'_i \text{ are all rational} \\ 0 & \text{if } x'_i \text{ are all irrational.} \end{cases}$$

We can always choose x'_i to be in either case since the rationals and irrationals are both dense in \mathbb{R} . So there is no $A \in \mathbb{R}$ such that $|A - S| < \epsilon$, no matter how small we take δ to be.

Remark. The function f from the previous example is not Riemann integrable, but it is Lebesgue integrable. In fact,

$$L = \int_a^b f(x) dx = 0$$

with respect to the Lebesgue measure. This is because the set of rational numbers \mathbb{Q} has measure zero.

5.3 Properties of the Riemann Integral

Proposition 5.1. *We have the following linearity properties of the Riemann integral:*

1. *If $f, g : [a, b] \rightarrow \mathbb{R}$ are Riemann integrable, then $f \pm g$ are also integrable and*

$$\int_a^b (f \pm g) dx = \int_a^b f(x) dx \pm \int_a^b g(x) dx$$

2. *For any $c \in \mathbb{R}$, cf is integrable and*

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

Proof. See textbook, fairly straightforward. □

Remark. Since we only discuss Riemann integration in this class, we will sometimes simply say “integrable” instead of “Riemann integrable.”

Proposition 5.2. *If $f : [a, b] \rightarrow \mathbb{R}$ is integrable and $f(x) \geq 0$, then*

$$\int_a^b f(x) dx \geq 0.$$

Proof. Let

$$A = \int_a^b f(x) dx.$$

Then for any $\epsilon > 0$, there exists $\delta > 0$ such that for any partition of width $< \delta$, we have $|A - S| < \epsilon$. But

$$S = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}) \geq 0,$$

Then we have $A > S - \epsilon \geq -\epsilon$, so taking $\epsilon \rightarrow 0$ gives $A \geq 0$. □

Corollary 5.0.1. *If $f, g : [a, b] \rightarrow \mathbb{R}$ are integrable and $f(x) \geq g(x)$ for all $x \in [a, b]$, then*

$$\int_a^b f(x) \, dx \geq \int_a^b g(x) \, dx.$$

Proof. By linearity,

$$\int_a^b f(x) \, dx - \int_a^b g(x) \, dx = \int_a^b (f(x) - g(x)) \, dx \geq 0$$

since $f(x) - g(x) \geq 0$ by assumption. □

Corollary 5.0.2. *If $f : [a, b] \rightarrow \mathbb{R}$ is integrable and $m \leq f(x) \leq M$ for all $x \in [a, b]$, then*

$$m(b - a) \leq \int_a^b f(x) \, dx \leq M(b - a).$$

Lecture 6

Jan. 25 — Riemann Integrability

6.1 Conditions for Integrability

Lemma 6.1. *A function $f : [a, b] \rightarrow \mathbb{R}$ is integrable if and only if for any $\epsilon > 0$, there exists $\delta > 0$ such that $|S_1 - S_2| < \epsilon$ whenever S_1 and S_2 are Riemann sums for partitions of width less than δ .*

Proof. (\Rightarrow) If f is integrable, then for any $\epsilon > 0$, there exists $\delta > 0$ such that

$$\left| S - \int_a^b f(x) dx \right| < \frac{\epsilon}{2}$$

for any Riemann sum S of a partition with width less than δ . Then

$$|S_1 - S_2| \leq \left| S_1 - \int_a^b f(x) dx \right| + \left| S_2 - \int_a^b f(x) dx \right| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon,$$

as desired.

(\Leftarrow) Take the special partition into intervals of equal length, with width $(b-a)/n$. Pick the middle point in each interval, and let

$$S_n = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1})$$

be the corresponding Riemann sum. Now we check that $\{S_n\}_{n=1}^\infty$ is a Cauchy sequence. This is because for any $\epsilon > 0$, if N is large enough, then for any $n, m \geq N$, we have $|S_n - S_m| < \epsilon$ if $1/N < \delta$. Then $\{S_n\}_{n=1}^\infty$ converges, so let $\lim_{n \rightarrow \infty} S_n = A$. Now for any $\epsilon > 0$, there exists $\delta > 0$ such that for any Riemann sum S with width $< \delta$, if $1/n < \delta$, then $|S_n - S| < \epsilon/2$. So

$$|S - A| \leq |S_n - S| + |S_n - A| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon,$$

if n is large enough. Thus

$$A = \int_a^b f(x) dx$$

exists and is the Riemann integral of f . □

Remark. Recall the step function $f : [a, b] \rightarrow \mathbb{R}$ given by

$$f(x) = \begin{cases} 1 & \text{if } x \in (\alpha, \beta) \subseteq [a, b] \\ 0 & \text{if } x \notin (\alpha, \beta). \end{cases}$$

Last time we saw that f is integrable and that

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

Now let us consider a more general step function. We call f a *step function* on $[a, b]$ if there exists a partition $x_0 < x_1 < \cdots < x_n$ of $[a, b]$ such that $f(x)$ is constant on each subinterval (x_{i-1}, x_i) .

Lemma 6.2. *If $f : [a, b] \rightarrow \mathbb{R}$ is a step function for a partition $x_0 < x_1 < \cdots < x_n$ and $f(x) = c_i$ when $x \in (x_{i-1}, x_i)$, then f is integrable and*

$$\int_a^b f(x) dx = \sum_{i=1}^n c_i(x_i - x_{i-1}).$$

Proof. Define

$$\varphi_i(x) = \begin{cases} 1 & \text{if } x \in (x_{i-1}, x_i) \\ 0 & \text{otherwise.} \end{cases}$$

Now let

$$h = f - \sum_{i=1}^n c_i \varphi_i.$$

Then $h(x)$ is nonzero only at $\{x_i\}_{i=0}^n$. Each φ_i is integrable and h is integrable with

$$\int_a^b h(x) dx = 0,$$

so f is also integrable and

$$\int_a^b f(x) dx = \sum_{i=1}^n c_i \int_a^b \varphi_i(x) dx = \sum_{i=1}^n c_i(x_i - x_{i-1})$$

by linearity and the integral of a simple step function that we calculated before. □

Proposition 6.1. *A function $f : [a, b] \rightarrow \mathbb{R}$ is integrable if and only if for any $\epsilon > 0$, there exist step functions f_1, f_2 such that $f_1(x) \leq f(x) \leq f_2(x)$ for all $x \in [a, b]$ and*

$$\int_a^b (f_2 - f_1) dx < \epsilon.$$

Proof. (\Leftarrow) For any $\epsilon > 0$, choose step functions f_1, f_2 such that

$$\int_a^b (f_2 - f_1) dx < \frac{\epsilon}{3}.$$

Then there exists $\delta > 0$ such that for any partition with width $< \delta$, the Riemann sums S_1, S_2 for f_1, f_2 satisfy

$$|S_1 - \int_a^b f_1(x) dx| < \frac{\epsilon}{3} \quad \text{and} \quad |S_2 - \int_a^b f_2(x) dx| < \frac{\epsilon}{3}.$$

So for any partition width $< \delta$, the Riemann sum of f is

$$S = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}),$$

and $S_1 \leq S \leq S_2$ since

$$S_1 = \sum_{i=1}^n f_1(x'_i)(x_i - x_{i-1}) \quad \text{and} \quad S_2 = \sum_{i=1}^n f_2(x'_i)(x_i - x_{i-1}).$$

So S is in the interval (S_1, S_2) , which has length $< \epsilon$ by the triangle inequality on the previous results. For any two Riemann sums of f with partitions of width $< \delta$, we have $|S' - S''| < \epsilon$. Thus f is integrable.

(\Rightarrow) First we show that f is bounded in $[a, b]$. This is because for any $\epsilon > 0$, there exists $\delta > 0$ such that any two Riemann sums S_1, S_2 corresponding to partitions of width $< \delta$ satisfy $|S_1 - S_2| < \epsilon$. Let

$$S_1 = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}),$$

and replace $x'_{i_0} \in (x_{i_0-1}, x_{i_0})$ with $x''_{i_0} \in (x_{i_0-1}, x_{i_0})$. Keep x'_i for $i \neq i_0$. Define this new Riemann sum to be S_2 . Then

$$|S_2 - S_1| \leq |f(x''_{i_0}) - f(x'_{i_0})|(x_{i_0} - x_{i_0-1}) < \epsilon,$$

so that

$$|f(x''_{i_0})| \leq |f(x'_{i_0})| + \frac{\epsilon}{x_{i_0} - x_{i_0-1}},$$

i.e. f is bounded in (x_{i_0-1}, x_{i_0}) since x''_{i_0} was arbitrary. Since we also picked i_0 arbitrarily, we can repeat this for any interval to conclude that f is bounded in $[a, b]$.

Now for any partition $x_0 < x_1 < \dots < x_n$ with width $< \delta$, define

$$m_i = \inf\{f(x) : x \in (x_{i-1}, x_i)\} \quad \text{and} \quad M_i = \sup\{f(x) : x \in (x_{i-1}, x_i)\}.$$

Define the step function

$$f_1(x) = \begin{cases} m_i & \text{if } x \in (x_{i-1}, x_i) \\ \min\{m_1, \dots, m_n\} & \text{if } x = x_i \text{ for } i = 0, \dots, n. \end{cases}$$

Similarly define

$$f_2(x) = \begin{cases} M_i & \text{if } x \in (x_{i-1}, x_i) \\ \max\{M_1, \dots, M_n\} & \text{if } x = x_i \text{ for } i = 0, \dots, n. \end{cases}$$

Observe that $f_1(x) \leq f(x) \leq f_2(x)$ for any $x \in [a, b]$ by construction. Now we verify that

$$\int_a^b (f_2 - f_1) dx < \epsilon$$

if $\delta > 0$ is small enough. This is because for any $\eta > 0$, there exists $x'_i, x''_i \in [x_{i-1}, x_i]$ such that $f(x'_i) < m_i + \eta$ and $f(x''_i) > M_i - \eta$. Then

$$\sum_{i=1}^n (f(x''_i) - f(x'_i))(x_i - x_{i-1}) > \sum_{i=1}^n (M_i - m_i - 2\eta)(x_i - x_{i-1}) = \int_a^b (f_2 - f_1) dx - 2\eta(b - a).$$

If $\delta > 0$ is small enough, then

$$\sum_{i=1}^n (f(x'_i) - f(x''_i))(x_i - x_{i-1}) < \epsilon$$

since this is a difference of two Riemann sums with partitions of width $< \delta$. Thus

$$\int_a^b (f_2 - f_1) dx < \epsilon + 2\eta(b - a).$$

But η was arbitrary, so taking $\eta \rightarrow 0$ gives the desired result. \square

Corollary 6.0.1. *If $f : [a, b] \rightarrow \mathbb{R}$ is integrable, then it is bounded.*

Proof. This was shown in the proof of the previous proposition. \square

Theorem 6.1. *If $f : [a, b] \rightarrow \mathbb{R}$ is continuous, then f is integrable.*

Proof. Since f is continuous on the compact set $[a, b]$, it is uniformly continuous. So for any $\epsilon > 0$, there exists $\delta > 0$ such that for any $x', x'' \in [a, b]$, we have $|f(x') - f(x'')| < \epsilon$ whenever $|x' - x''| < \delta$. Now let S_1, S_2 be two Riemann sums with partitions of width $< \delta$. Assume without loss of generality that S_1, S_2 are defined over the same partition (we can always combine two partitions to give a finer partition, if necessary). Let

$$S_1 = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}) \quad \text{and} \quad S_2 = \sum_{i=1}^n f(x''_i)(x_i - x_{i-1}).$$

Then

$$|S_1 - S_2| \leq \sum_{i=1}^n |f(x'_i) - f(x''_i)|(x_i - x_{i-1}) < \epsilon \sum_{i=1}^n (x_i - x_{i-1}) = \epsilon(b - a).$$

Since $\epsilon > 0$ was arbitrary, we conclude that f is integrable by Lemma 6.1. \square

6.2 The Fundamental Theorem of Calculus

Theorem 6.2 (Fundamental theorem of calculus). *If $f : [a, b] \rightarrow \mathbb{R}$ has anti-derivative $F : [a, b] \rightarrow \mathbb{R}$ and $f \in \mathcal{R}([a, b])$,¹ then*

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

Proof. Since f is integrable, let

$$A = \int_a^b f(x) dx.$$

For any $\epsilon > 0$, there exists $\delta > 0$ such that for any Riemann sum S with partition of width $< \delta$, we have $|S - A| < \epsilon$. Let $x_0 < x_1 < \dots < x_n$ be a partition of width $< \delta$. Then by telescoping,

$$F(b) - F(a) = \sum_{i=1}^n (F(x_i) - F(x_{i-1})) = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1})$$

¹Here $\mathcal{R}([a, b])$ is the class of Riemann integrable functions on $[a, b]$.

by Lagrange's mean value theorem, where $x'_i \in (x_{i-1}, x_i)$. Then

$$|F(b) - F(a) - A| = |S - A| < \epsilon,$$

so letting $\epsilon \rightarrow 0$ gives $F(b) - F(a) = A$. □

Remark. The fundamental theorem of calculus requires both being Riemann integrable and having an anti-derivative, which do not always overlap. In fact, neither is a subset of the other.

Example 6.0.1. The step function

$$f(x) = \begin{cases} -1 & \text{if } 0 \leq x \leq 1 \\ 1 & \text{if } 1 < x \leq 2 \end{cases}$$

is integrable but has no anti-derivative.

Example 6.0.2. Define

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

Then we have

$$F'(x) = f(x) = \begin{cases} 0 & \text{if } x = 0 \\ (-2/x)(\cos(1/x^2)) + 2x \sin(1/x^2) & \text{if } x \neq 0. \end{cases}$$

We can check that $F'(0) = 0$ via the definition of the derivative. Note that f has an anti-derivative, namely F . However, f is not integrable since it is not bounded near $x = 0$.

Lecture 7

Jan. 30 — Riemann Integrability, Part 2

7.1 Conditions for an Anti-Derivative

Lemma 7.1. *Let $c \in (a, b)$. Then $f \in \mathcal{R}([a, b])$ if and only if $f \in \mathcal{R}([a, c])$ and $f \in \mathcal{R}([c, b])$. Moreover,*

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

Proof. (\Rightarrow) If $f \in \mathcal{R}([a, b])$, then for any $\epsilon > 0$, there exist two step functions f_1, f_2 such that $f_1 \leq f \leq f_2$ and

$$\int_a^b (f_2 - f_1) dx < \epsilon.$$

Let f_1, f_2 be the restrictions to $[a, c]$. Then still $f_1 \leq f \leq f_2$ on $[a, c]$ and

$$\int_a^c (f_2 - f_1) \leq \int_a^b (f_2 - f_1) < \epsilon$$

since $f_2 - f_1$ is a nonnegative step function. (Note that the desired result is easy to verify for step functions.) So $f \in \mathcal{R}([a, c])$, and the same argument works to show that $f \in \mathcal{R}([c, b])$.

(\Leftarrow) If $f \in \mathcal{R}([a, c])$ and $f \in \mathcal{R}([c, b])$, then for any $\epsilon > 0$, there exist step functions g_1, g_2, h_1, h_2 such that $g_1 \leq f \leq g_2$ on $[a, c]$, $h_1 \leq f \leq h_2$ on $[c, b]$, and

$$\int_a^c (g_2 - g_1) dx < \epsilon, \quad \int_c^b (h_2 - h_1) dx < \epsilon.$$

Now define

$$f_i = \begin{cases} g_i & \text{if } x \in [a, c) \\ h_i & \text{if } x \in [c, b] \end{cases}$$

for $i = 1, 2$. Then $f_1 \leq f \leq f_2$ on $[a, b]$, and

$$\int_a^b (f_2 - f_1) dx = \int_a^c (g_2 - g_1) dx + \int_c^b (h_2 - h_1) dx < 2\epsilon,$$

so $f \in \mathcal{R}([a, b])$. Now to prove (*), note that $f \in \mathcal{R}([a, c])$, so for any $\epsilon > 0$ there exist Riemann sums S_1 on $[a, c]$ and S_2 on $[c, b]$ such that

$$|S_1 - \int_a^c f(x) dx| < \frac{\epsilon}{3}, \quad |S_2 - \int_c^b f(x) dx| < \frac{\epsilon}{3}.$$

Now choose $\delta > 0$ such that if the Riemann sum S has partition with width $< \delta$, then

$$|S - \int_a^c f(x) dx| < \frac{\epsilon}{3}, \quad |S - \int_c^b f(x) dx| < \frac{\epsilon}{3}, \quad |S - \int_a^b f(x) dx| < \frac{\epsilon}{3}.$$

Now combine S_1, S_2 on $[a, b]$ to be a Riemann sum $S = S_1 + S_2$, so that

$$|S - \int_a^b f(x) dx| < \frac{\epsilon}{3}.$$

By the triangle inequality on the previous results,

$$\left| \int_a^b f(x) dx - \left(\int_a^c f(x) dx + \int_c^b f(x) dx \right) \right| < \epsilon.$$

Since ϵ is arbitrarily small, we conclude that

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

as desired. □

Remark. The formula $(*)$ is true for any three numbers a, b, c , as long as f is integrable. This is because by convention, if $a > b$, then

$$\int_a^b f(x) dx = - \int_b^a f(x) dx.$$

Theorem 7.1. If $f : [a, b] \rightarrow \mathbb{R}$ is continuous, then¹

$$F(x) = \int_a^x f(\xi) d\xi$$

is an anti-derivative of f .

Proof. For any $x_0 \in (a, b)$, we check that $F'(x_0) = f(x_0)$. We can compute using Lemma 7.1 that

$$\begin{aligned} \left| \frac{F(x_0 + h) - F(x_0)}{h} - f(x_0) \right| &= \left| \frac{1}{h} \left(\int_a^{x_0+h} f(x) dx - \int_a^{x_0} f(x) dx \right) - f(x_0) \right| \\ &= \left| \frac{1}{h} \int_{x_0}^{x_0+h} f(x) dx - f(x_0) \right| = \left| \frac{1}{h} \int_{x_0}^{x_0+h} (f(x) - f(x_0)) dx \right|. \end{aligned}$$

The last step is from observing

$$f(x_0) = \frac{1}{h} \int_{x_0}^{x_0+h} f(x_0) dx.$$

Since f is continuous, for any $\epsilon > 0$, there exists δ such that if $|x_0 - x| < \delta$, then $|f(x) - f(x_0)| < \epsilon$. This gives

$$\left| \frac{1}{h} \int_{x_0}^{x_0+h} (f(x) - f(x_0)) dx \right| \leq \frac{1}{h} \int_{x_0}^{x_0+h} |f(x) - f(x_0)| dx \leq \frac{\epsilon h}{h} = \epsilon$$

if $|h| < \delta$. Thus,

$$\lim_{h \rightarrow 0} \frac{F(x_0 + h) - F(x_0)}{h} - f(x_0) = f(x_0),$$

so we indeed have $F'(x_0) = f(x_0)$. □

¹Note that this integral is well-defined since any continuous function is integrable, and a continuous function restricted to a subset of its domain, i.e. $[a, x] \subseteq [a, b]$, remains continuous.

7.2 More Conditions for Integrability

Definition 7.1. Let $f : [a, b] \rightarrow \mathbb{R}$ be bounded and $x_0 < x_1 < \cdots < x_n$ be a partition of $[a, b]$. Define

$$\omega_i = \sup\{|f(x) - f(y)| : x, y \in [x_{i-1}, x_i]\}$$

for $i = 1, 2, \dots, n$. We will call this the *oscillation amplitude* of f .

Theorem 7.2. A function $f : [a, b] \rightarrow \mathbb{R}$ is integrable if and only if for any $\epsilon > 0$, there exists $\delta > 0$ such that for any partition with width $< \delta$, we have

$$\sum_{i=1}^n \omega_i \Delta x_i < \epsilon,$$

where $\Delta x_i = x_i - x_{i-1}$.

Proof. (\Leftarrow) For any $\epsilon > 0$, choose any two Riemann sums S_1, S_2 over partitions with width $< \delta$. Assume without loss of generality that S_1 and S_2 are defined over the same (maybe refined) partition. Let

$$S_1 = \sum_{i=1}^n f(x'_i)(x_i - x_{i-1}), \quad S_2 = \sum_{i=1}^n f(x''_i)(x_i - x_{i-1}).$$

Then we have

$$|S_1 - S_2| \leq \sum_{i=1}^n |f(x'_i) - f(x''_i)| \Delta x_i \leq \sum_{i=1}^n \omega_i \Delta x_i < \epsilon.$$

Then by Lemma 6.1, we conclude that f is integrable.

(\Rightarrow) Since f is integrable, by Lemma 6.1 we have that for any $\epsilon > 0$, there exists $\delta > 0$ such that for any two Riemann sums S_1, S_2 over partitions of width $< \delta$, we have $|S_1 - S_2| < \epsilon$. In the interval $[x_{i-1}, x_i]$, let

$$M_i = \sup_{x \in [x_{i-1}, x_i]} |f(x)|, \quad m_i = \inf_{x \in [x_{i-1}, x_i]} |f(x)|.$$

In particular note that $\omega_i = M_i - m_i$. Now for any $\eta > 0$, there exist $x'_i, x''_i \in [x_{i-1}, x_i]$ such that

$$f(x'_i) > M_i - \eta, \quad f(x''_i) < m_i + \eta.$$

Let

$$S_1 = \sum_{i=1}^n f(x'_i) \Delta x_i, \quad S_2 = \sum_{i=1}^n f(x''_i) \Delta x_i.$$

Then we have

$$|S_1 - S_2| \leq \left| \sum_{i=1}^n (f(x'_i) - f(x''_i)) \Delta x_i \right|$$

Note that $f(x'_i) - f(x''_i) \geq M_i - m_i - 2\eta$ for η sufficiently small. Thus

$$|S_1 - S_2| \geq \sum_{i=1}^n \omega_i \Delta x_i - 2\eta \sum_{i=1}^n \Delta x_i,$$

so that

$$\sum_{i=1}^n \omega_i \Delta x_i \leq |S_1 - S_2| + 2\eta(b - a) < \epsilon + 2\eta(b - a).$$

From here letting $\eta \rightarrow 0$ gives the desired result. □

Theorem 7.3. *A function $f : [a, b] \rightarrow \mathbb{R}$ is integrable if and only if for any $\epsilon > 0$, there exists a partition such that*

$$\sum_{i=1}^n \omega_i(f) \Delta x_i < \epsilon.$$

Proof. (\Rightarrow) This is immediate from the previous theorem.

(\Leftarrow) We show that for any $\epsilon > 0$, there exists $\delta > 0$ such that for any partition with width $< \delta$, we have

$$\sum_{i=1}^n \omega_i(f) \Delta x_i < \epsilon.$$

This will imply that f is integrable by the previous theorem. Let $y_0 < y_1 < \cdots < y_m$ be the partition satisfying

$$\sum_{j=1}^m \omega_j(f) \Delta y_j < \epsilon,$$

and choose

$$\delta < \frac{1}{4} \min_{j=1, \dots, m} \Delta y_j.$$

For any partition $x_0 < \cdots < x_n$ with width $< \delta$. We divide the intervals $[x_{i-1}, x_i]$ into two classes. The first case (1) is where $[x_{i-1}, x_i]$ is contained in one of the $[y_{j-1}, y_j]$, and the second case (2) is where $[x_{i-1}, x_i]$ contains an interior point y_j . In the first case, we have

$$\sum_{(1)} \omega_i(f) \Delta x_i \leq \sum_{j=1}^m \omega_j(f) \Delta y_j.$$

For the second case, since $[x_{i-1}, x_i]$ contains an interior point y_j but $\delta < \Delta y_j, \Delta y_{j+1}$, we must have

$$y_{j-1} < x_{i-1} < y_j < x_i < y_{j+1},$$

so that

$$\omega_i(f) \Delta x_i \leq \frac{1}{2} (\omega_j(f) \Delta y_j + \omega_{j+1}(f) \Delta y_{j+1}).$$

This implies

$$\sum_{(2)} \omega_i(f) \Delta x_i \leq \frac{1}{2} \sum_{j=1}^m \omega_j(f) \Delta y_j.$$

Thus

$$\sum_{i=1}^n \omega_i(f) \Delta x_i = \sum_{(1)} \omega_i(f) \Delta x_i + \sum_{(2)} \omega_i(f) \Delta x_i \leq 2 \sum_{j=1}^m \omega_j(f) \Delta y_j < 2\epsilon,$$

so that f is integrable. □

Lecture 8

Feb. 1 — Riemann Integrability, Part 3

8.1 Even More Conditions for Integrability

Example 8.0.1. If $f(x)$ is monotone on $[a, b]$, then $f \in \mathcal{R}([a, b])$.

Proof. Suppose $f(x)$ is monotone increasing on $[a, b]$ and $f(x)$ is not constant (since the result is trivial if f is constant). Then $f(a) \leq f(x) \leq f(b)$. For any $\epsilon > 0$, for any partition $x_0 < \cdots < x_n$ with width

$$\delta < \frac{\epsilon}{f(b) - f(a)},$$

we have on $[x_{i-1}, x_i]$ that $M_i = f(x_i)$ and $f(x_{i-1}) = m_i$ since f is monotone. Then

$$\omega_i(f) = f(x_i) - f(x_{i-1}) = M_i - m_i.$$

Thus

$$\sum_{i=1}^n \omega_i(f) \Delta x_i = \sum_{i=1}^n (f(x_i) - f(x_{i-1})) \Delta x_i < \frac{\epsilon}{f(b) - f(a)} \sum_{i=1}^n (f(x_i) - f(x_{i-1})) = \epsilon$$

since the sum telescopes and comes out to $f(b) - f(a)$. Thus f is integrable. \square

Theorem 8.1 (Du Bois-Reymond). *Let f be bounded on $[a, b]$. Then $f \in \mathcal{R}([a, b])$ if and only if for any $\epsilon, a > 0$, there exists a partition such that the total length of subintervals with $\omega_i(f) \geq \epsilon$ is $< a$.*

Proof. For any partition $x_0 < \cdots < x_n$, split

$$\sum_{i=1}^n \omega_i(f) \Delta x_i = \sum_{(A)} \omega_i(f) \Delta x_i + \sum_{(B)} \omega_i(f) \Delta x_i$$

where (A) is over subintervals with width $\omega_i(f) < \epsilon$ and (B) is over subintervals with width $\omega_i(f) \geq \epsilon$.

(\Rightarrow) Let

$$\Omega = \sup_{x, y \in [a, b]} |f(x) - f(y)|.$$

For any $\epsilon > 0$, for

$$\epsilon_1 = \frac{\epsilon}{2(b-a)} \quad \text{and} \quad a = \frac{\epsilon}{2\Omega},$$

by assumption there exists a partition $x_0 < \cdots < x_n$ such that

$$\begin{aligned} \sum_{i=1}^n \omega_i(f) \Delta x_i &= \sum_{(A)} \omega_i(f) \Delta x_i + \sum_{(B)} \omega_i(f) \Delta x_i \\ &< \frac{\epsilon}{2(b-a)} \sum_{(a)} \Delta x_i + \Omega \sum_{(B)} \Delta x_i < \frac{\epsilon}{2(b-a)} (b-a) + \Omega \frac{\epsilon}{2\Omega} = \epsilon. \end{aligned}$$

So we see that $f \in \mathcal{R}([a, b])$ as desired.

(\Rightarrow) If $f \in \mathcal{R}([a, b])$, then for any $\epsilon, a > 0$, there exists a partition $x_0 < \cdots < x_n$ such that

$$\sum_{i=1}^n \omega_i(f) \Delta x_i < a\epsilon.$$

Then we have

$$\epsilon \sum_{(B)} \Delta x_i \leq \sum_{(B)} \omega_i(f) \Delta x_i < a\epsilon \implies \sum_{(B)} \Delta x_i < a,$$

which shows the desired result. \square

Corollary 8.1.1. *If $f : [a, b] \rightarrow \mathbb{R}$ is bounded and has only finitely many discontinuity points, then $f \in \mathcal{R}([a, b])$.*

Proof. Suppose $f(x)$ has p discontinuity points on $[a, b]$ and $m \leq f(x) \leq M$ for all $x \in [a, b]$. Then for any $\epsilon > 0$, first (1) we construct p small open intervals on $[a, b]$ containing the p discontinuity points with

$$\text{total length} < \frac{\epsilon}{2(M-m)}.$$

Next (2) for any subintervals in $[a, b]$ excluding the above p subintervals, f is continuous on them, so there exists a partition such that

$$\sum_{(2)} \omega_i(f) \Delta x_i < \frac{\epsilon}{2}.$$

Now combine (1) and (2) to get

$$\sum_{i=1}^n \omega_i(f) \Delta x_i = \sum_{(1)} \omega_i(f) \Delta x_i + \sum_{(2)} \omega_i(f) \Delta x_i < (M-m) \frac{\epsilon}{2(M-m)} + \frac{\epsilon}{2} = \epsilon.$$

Thus $f \in \mathcal{R}([a, b])$, as desired. \square

Example 8.0.2. Consider

$$f(x) = \begin{cases} \sin(1/x) & \text{if } x \neq 0 \\ A & \text{if } x = 0 \end{cases}$$

for any constant $A \in \mathbb{R}$. Then by the previous corollary, $f \in \mathcal{R}([0, 1])$.

Theorem 8.2. *If $f, g \in \mathcal{R}([a, b])$, then $fg \in \mathcal{R}([a, b])$.*

Proof. Since f, g are integrable, they are bounded. So assume $|f|, |g| \leq M$. Then for any $\epsilon > 0$, there exists $\delta > 0$ such that for any partition of width $< \delta$, we have

$$\sum_{i=1}^n \omega_i(f) \Delta x_i < \frac{\epsilon}{2M}, \quad \sum_{i=1}^n \omega_i(g) \Delta x_i < \frac{\epsilon}{2M}.$$

Notice

$$\omega_i(fg) \leq M(\omega_i(f) + \omega_i(g))$$

because

$$\begin{aligned} |f(x)g(x) - f(y)g(y)| &\leq |g(x)||f(x) - f(y)| + |f(y)||g(x) - g(y)| \\ &\leq M(|f(x) - f(y)| + |g(x) - g(y)|). \end{aligned}$$

Taking suprememes over $x, y \in [x_{i-1}, x_i]$ from here gives $\omega_i(fg) \leq M(\omega_i(f) + \omega_i(g))$. Then

$$\sum_{i=1}^n \omega_i(fg) \Delta x_i \leq M \left(\sum_{i=1}^n \omega_i(f) \Delta x_i + \sum_{i=1}^n \omega_i(g) \Delta x_i \right) < M \left(\frac{\epsilon}{2M} + \frac{\epsilon}{2M} \right) = \epsilon.$$

Thus $fg \in \mathcal{R}([a, b])$ as desired. □

Theorem 8.3. *If $f \in \mathcal{R}([a, b])$, then $|f| \in \mathcal{R}([a, b])$ and*

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

Proof. Since $f \in \mathcal{R}([a, b])$, for any $\epsilon > 0$ there exists a partition $x_0 < \cdots < x_n$ such that

$$\sum_{i=1}^n \omega_i(f) \Delta x_i < \epsilon.$$

Since

$$||f(x)| - |f(y)|| \leq |f(x) - f(y)|,$$

taking supremums over $x, y \in [x_{i-1}, x_i]$ gives $\omega_i(|f|) \leq \omega_i(f)$. Then

$$\sum_{i=1}^n \omega_i(|f|) \Delta x_i \leq \sum_{i=1}^n \omega_i(f) \Delta x_i < \epsilon.$$

So we indeed have $|f| \in \mathcal{R}([a, b])$. Now observe that $-|f| \leq f \leq |f|$. After integrating, we get

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

This immediately implies the desired result. □

Example 8.0.3 (Cauchy-Schwarz). If $f, g \in \mathcal{R}([a, b])$, then

$$\left| \int_a^b f(x)g(x) dx \right| \leq \left(\int_a^b f(x)^2 dx \right)^{1/2} \left(\int_a^b g(x)^2 dx \right)^{1/2}. \quad (*)$$

Proof. Let

$$A = \int_a^b f^2 dx, \quad B = \int_a^b |fg| dx, \quad C = \int_a^b g^2 dx.$$

Note that it suffices to show that $B^2 \leq AC$, which will imply $(*)$ by the previous theorem. Then

$$0 \leq \int_a^b (t|f| - |g|)^2 dx = At^2 - 2Bt + C$$

for any $t \in \mathbb{R}$. So the discriminant must satisfy $(2B)^2 - 4AC \leq 0$, which gives $B^2 \leq AC$ as desired. \square

Example 8.0.4 (Riemann-Lebesgue lemma). If $f \in \mathcal{R}([a, b])$, then

$$\lim_{\lambda \rightarrow \infty} \int_a^b f(x) \sin(\lambda x) dx = 0.$$

Proof. Since $f \in \mathcal{R}([a, b])$, for any $\epsilon > 0$ there exists a partition $x_0 < \cdots < x_n$ of $[a, b]$ such that

$$\sum_{i=1}^n \omega_i(f) \Delta x_i < \frac{\epsilon}{2}.$$

Also assume $|f| \leq M$ on $[a, b]$ since f is integrable. Then we choose

$$\lambda > \frac{4nM}{\epsilon}.$$

We can estimate

$$\begin{aligned} \left| \int_a^b f(x) \sin(\lambda x) dx \right| &= \left| \sum_{i=1}^n \int_{x_{i-1}}^{x_i} (f(x) - f(x_i) + f(x_i)) \sin(\lambda x) dx \right| \\ &\leq \sum_{i=1}^n |f(x_i)| \left| \int_{x_{i-1}}^{x_i} \sin(\lambda x) dx \right| + \sum_{i=1}^n \int_{x_{i-1}}^{x_i} \underbrace{|f(x) - f(x_i)|}_{\leq \omega_i(f)} \underbrace{|\sin(\lambda x)|}_{\leq 1} dx \\ &\leq M \sum_{i=1}^n \frac{\overbrace{|\cos(\lambda x_i) - \cos(\lambda x_{i-1})|}^{\leq 2}}{\lambda} + \sum_{i=1}^n \int_{x_{i-1}}^{x_i} \omega_i(f) dx \\ &\leq M \frac{2n}{\lambda} + \sum_{i=1}^n \omega_i(f) \Delta x_i < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon. \end{aligned}$$

So as $\lambda \rightarrow \infty$, the integral goes to 0. \square

Remark. Recall that

$$f(x) = \begin{cases} 0 & \text{if } x \text{ is irrational} \\ 1 & \text{if } x \text{ is rational} \end{cases}$$

is not Riemann integrable, but we might expect that this should integrate to 0. The Lebesgue integral will fix this, which was discovered much later.

Lecture 9

Feb. 6 — Exchange of Limit Operations

9.1 Motivation

If we have a sequence of functions $\{f_n\}$ where $f_n \rightarrow f$ pointwise, then does

$$\int_a^b f_n dx \rightarrow \int_a^b f dx$$

if each f_n is integrable? Does $f'_n \rightarrow f'$ if f_n is differentiable?

Example 9.0.1. Define

$$f_n(x) = \begin{cases} 4n^2x & \text{if } x \in [0, 1/2n] \\ 4n - 4n^2x & \text{if } x \in (1/2n, 1/n) \\ 0 & \text{if } x \in [1/n, 1], \end{cases}$$

where the graph of f_n looks like a triangle with peak at $x = 1/2n$ and height $2n$. When we let $n \rightarrow \infty$, we see that for any $x \in [0, 1]$, we have $f_n(x) \rightarrow 0$. But

$$\int_0^1 f_n(x) dx = \text{area of triangle} = \frac{1}{2}(2n) \cdot \frac{1}{n} = 1.$$

So we see that in this case,

$$\lim_{n \rightarrow \infty} \int_0^1 f_n dx \neq \int_0^1 \lim_{n \rightarrow \infty} f_n dx.$$

9.2 Exchange of the Limit and Integral

Theorem 9.1. Let f_1, \dots, f_n, \dots be a uniformly convergent sequence of continuous functions on $[a, b]$. Then

$$\int_a^b \lim_{n \rightarrow \infty} f_n(x) dx = \lim_{n \rightarrow \infty} \int_a^b f_n(x) dx.$$

Proof. Suppose that $f_n \rightarrow f$ uniformly. By definition of uniform convergence, for any $\epsilon > 0$ there exists N such that if $n \geq N$, then

$$\max_{x \in [a, b]} |f_n(x) - f(x)| < \frac{\epsilon}{b - a}$$

Each $f_n \rightarrow f$ uniformly and each f_n is continuous, f is also continuous. In particular, f is integrable and

$$-\frac{\epsilon}{b - a} < f_n(x) - f(x) < \frac{\epsilon}{b - a},$$

so integrating on both sides gives

$$-\epsilon < \int_a^b f_n(x) dx - \int_a^b f(x) dx < \epsilon \implies \left| \int_a^b f_n(x) dx - \int_a^b f(x) dx \right| < \epsilon.$$

Then this implies

$$\lim_{n \rightarrow \infty} \int_a^b f_n(x) dx = \int_a^b f(x) dx,$$

as desired. \square

Remark. The previous theorem still holds even if each f_n is only Riemann integrable. The only thing we need to check is that the limit function f is also Riemann integrable. This is because for any $\epsilon > 0$, if n is large enough,

$$-\frac{\epsilon}{3(b-a)} + f_n(x) \leq f(x) \leq f_n(x) + \frac{\epsilon}{3(b-a)}.$$

Since $f_n \in \mathcal{R}([a, b])$, there exist two step functions g_1, g_2 satisfying $g_1 \leq f_n \leq g_2$, and

$$\int_a^b (g_2 - g_1) < \frac{\epsilon}{3}.$$

Now note that

$$g_1(x) - \frac{\epsilon}{3(b-a)} \leq f(x) \leq g_2(x) + \frac{\epsilon}{3(b-a)},$$

so we see

$$\int_a^b \left[\left(g_2(x) + \frac{\epsilon}{3(b-a)} \right) - \left(g_1(x) - \frac{\epsilon}{3(b-a)} \right) \right] dx = \frac{\epsilon}{3} + \frac{2\epsilon}{3} = \epsilon.$$

This gives $f \in \mathcal{R}([a, b])$, so we can carry through the rest of the previous proof.

9.3 Exchange of the Limit and Derivative

Theorem 9.2. Let f_1, \dots, f_n, \dots be a sequence of functions on an open interval U in \mathbb{R} and that each f_n has a continuous derivative. Suppose $\{f'_n\}$ converges uniformly on U and for some $a \in U$, $\{f'_n(a)\}$ converges. Then

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

exists and $f(x)$ is differentiable. Furthermore, we have

$$f' = \lim_{n \rightarrow \infty} f'_n.$$

Proof. By the fundamental theorem of calculus, we have

$$\int_a^x f'_n(t) dt = f_n(x) - f_n(a). \quad (*)$$

Let $\lim_{n \rightarrow \infty} f'_n = g$, where g is continuous since $f'_n \rightarrow g$ uniformly and each f'_n is continuous. Then take $n \rightarrow \infty$ in $(*)$, where

$$\text{LHS} \rightarrow \int_a^x g(t) dt.$$

Let $\lim_{n \rightarrow \infty} f_n(x) = f(x)$, which exists by $(*)$. Then $\text{RHS} \rightarrow f(x) - f(a)$, so we see that

$$f(x) - f(a) = \int_a^x g(t) dt.$$

Then f is an anti-derivative of g , or in other words, $f' = g$ as desired. \square

9.4 Infinite Series

Definition 9.1. Suppose we have a sequence of numbers $a_1, a_2, a_3, \dots, a_n, \dots$. Then

$$a_1 + a_2 + a_3 + \dots + a_n + \dots = \sum_{n=1}^{\infty} a_n$$

is called an *infinite series*. We say the infinite series *converges* to A if the *partial sums*

$$S_m = \sum_{n=1}^m a_n$$

converge to A as $m \rightarrow \infty$.

Example 9.1.1 (Geometric series). For a fixed a , the series

$$\sum_{n=0}^{\infty} a^n = 1 + a + a^2 + \dots + a^n + \dots$$

converges if and only if $|a| < 1$, and the limit is $1/(1 - a)$. This is because

$$S_m = 1 + a + \dots + a^m = \frac{1 - a^{m+1}}{1 - a}.$$

If $|a| < 1$, then $a^{m+1} \rightarrow 0$ as $m \rightarrow \infty$, so $S_m \rightarrow 1/(1 - a)$. On the other hand, if $|a| > 1$, then $|a^{m+1}| \rightarrow \infty$ as $m \rightarrow \infty$. If $a = 1$, then

$$S_m = 1 + 1 + \dots + 1 = m,$$

so $S_m \rightarrow \infty$. If $a = -1$, then

$$\sum_{n=0}^{\infty} (-1)^n = 1 - 1 + 1 - 1 + \dots,$$

which diverges since its partial sums oscillate. So the condition is indeed necessary and sufficient.

Proposition 9.1. A series $\sum_{n=1}^{\infty} a_n$ converges if and only if for every $\epsilon > 0$, there exists integer N such that if $n > m \geq N$, then

$$|a_{m+1} + a_{m+2} + \dots + a_n| < \epsilon.$$

Proof. Let $S_m = \sum_{n=1}^m a_n$ be the partial sums. Then $\sum_{n=1}^{\infty} a_n$ converges if and only if $\{S_m\}$ is Cauchy. This is equivalent to say that for all $\epsilon > 0$, there exists N such that if $n > m \geq N$, then

$$|a_{m+1} + a_{m+2} + \dots + a_n| = |S_n - S_m| < \epsilon.$$

This is precisely the desired result. □

Corollary 9.2.1. If $\sum_{n=1}^{\infty} a_n$ converges, then $a_n \rightarrow 0$ as $n \rightarrow \infty$.

Proof. Take $m = n - 1$ in the previous proposition, which gives $|a_n| < \epsilon$ for $n \geq N + 1$. □

Corollary 9.2.2. If $\sum_{n=1}^{\infty} a_n$ and $\sum_{n=1}^{\infty} b_n$ differs in only finitely many terms, then the two series have the same convergence properties.

Proof. Simply take N larger than the last spot where the two series differ. Then the difference of partial sums in the previous proposition are the same for both series. \square

Example 9.1.2 (Harmonic series). The series

$$\sum_{n=1}^{\infty} \frac{1}{n} = 1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n} + \cdots$$

diverges. To see this, choose $n = 2m$ in the previous proposition and

$$a_{m+1} + a_{m+2} + \cdots + a_{2m} = \frac{1}{m+1} + \frac{1}{m+2} + \cdots + \frac{1}{2m} \geq \frac{1}{2m}m = \frac{1}{2}.$$

So the series must diverge.

Proposition 9.2. *If $a_n \geq 0$, then $\sum_{n=1}^{\infty} a_n$ either converges or has arbitrarily large partial sums, i.e. diverges to ∞ .*

Proof. Let $S_m = \sum_{n=1}^m a_n$. Since $a_n \geq 0$, we see that S_m is an increasing nonnegative sequence. Then by the monotone convergence theorem, $\{S_m\}$ converges if and only if it is bounded above. \square

Proposition 9.3 (Comparison test). *If $\sum_{n=1}^{\infty} a_n$ and $\sum_{n=1}^{\infty} b_n$ are two infinite series such that $|a_n| \leq b_n$ and $\sum_{n=1}^{\infty} b_n$ converges, then $\sum_{n=1}^{\infty} a_n$ converges and*

$$\left| \sum_{n=1}^{\infty} a_n \right| \leq \sum_{n=1}^{\infty} b_n.$$

Proof. If $\sum_{n=1}^{\infty} b_n$ converges, then for any $\epsilon > 0$, there exists N such that if $n > m \geq N$, we have

$$b_{m+1} + b_{m+2} + \cdots + b_n < \epsilon.$$

Then by the triangle inequality, we have

$$|a_{m+1} + a_{m+2} + \cdots + a_n| \leq |a_{m+1}| + |a_{m+2}| + \cdots + |a_n| \leq b_{m+1} + b_{m+2} + \cdots + b_n < \epsilon.$$

Thus $\sum_{n=1}^{\infty} a_n$ also converges. The last part is left as an exercise. \square

Example 9.1.3 (p -series). The series

$$\sum_{n=1}^{\infty} \frac{1}{n^p}$$

converges if and only if $p > 1$. We will show this with the integral test later.

Proposition 9.4 (Ratio test). *If $\sum_{n=1}^{\infty} a_n$ is a nonzero infinite series and there exists $\rho < 1$ such that*

$$\left| \frac{a_{n+1}}{a_n} \right| \leq \rho$$

for all n sufficiently large, then $\sum_{n=1}^{\infty} a_n$ converges. If

$$\left| \frac{a_{n+1}}{a_n} \right| \geq 1$$

for all n large enough, then the series diverges.

Proof. First we show the second part. If $|a_{n+1}| \geq |a_n|$ for $n \geq N$, then

$$|a_n| \geq |a_{n-1}| \geq \cdots \geq |a_N|.$$

Then $\{a_n\}$ does not converge to 0, so $\sum_{n=1}^{\infty} a_n$ diverges. Look up the first part, but it should just be a comparison to the geometric series with common ratio ρ . \square

Lecture 10

Feb. 8 — Infinite Series

10.1 Lots of Convergence Tests

10.1.1 The Comparison Test

Theorem 10.1 (Comparison test, second version). *Let $\sum_{n=1}^{\infty} a_n$ and $\sum_{n=1}^{\infty} b_n$ be two infinite series satisfying $0 \leq a_n \leq b_n$. Then*

1. *If $\sum_{n=1}^{\infty} b_n$ converges, then $\sum_{n=1}^{\infty} a_n$ converges.*
2. *If $\sum_{n=1}^{\infty} a_n$ diverges, then $\sum_{n=1}^{\infty} b_n$ diverges.*

Proof. (1) Let A_n and B_n be the partial sums of $\sum_{n=1}^{\infty} a_n$ and $\sum_{n=1}^{\infty} b_n$, respectively. Then B_n is bounded above since $\sum_{n=1}^{\infty} b_n$ converges. But $A_n \leq B_n$ since $0 \leq a_n \leq b_n$, so A_n is also bounded above. Now note that A_n is increasing since $a_n \geq 0$, so by the monotone convergence theorem, A_n must converge.

(2) Since A_n is increasing, $\sum_{n=1}^{\infty} a_n$ must diverge to ∞ , i.e. A_n is unbounded. But $A_n \leq B_n$, so B_n is also unbounded and thus we see that $\sum_{n=1}^{\infty} b_n$ diverges. \square

Remark. In the above theorem, (1) remains true if

- $0 \leq a_n \leq b_n$ when $n \geq n_0$
- $0 \leq a_n \leq Mb_n$ for some $M > 0$,
- or there exists $0 < d_n < M$ such that $0 \leq a_n \leq d_nb_n$.

Corollary 10.1.1. *If $a_n, b_n > 0$ and*

$$\frac{a_{n+1}}{a_n} \leq \frac{b_{n+1}}{b_n},$$

then $\sum_{n=1}^{\infty} b_n$ converges implies that $\sum_{n=1}^{\infty} a_n$ converges.

Proof. Let $d_n = a_n/b_n > 0$. Then

$$d_{n+1} = \frac{a_{n+1}}{b_{n+1}} \leq \frac{a_n}{b_n} = d_n,$$

which we can extend to $d_n \leq \dots \leq d_1$. Then $\{d_n\}$ is a bounded sequence, so $a_n = b_nd_n$, which implies the desired conclusion by the above remark. \square

Remark. If n large, $e^{an} \gg n^b \gg (\ln n)^c$ for any $a, b, c > 0$. In particular, $e^{an}/n^b \rightarrow \infty$ when $n \rightarrow \infty$.

Example 10.0.1. Determine the convergence of

1. $\sum_{n=2}^{\infty} \frac{1}{(\ln n)^p}$ for $p > 0$,
2. $\sum_{n=2}^{\infty} \frac{\ln(n!)}{n^p}$ for $p > 0$,
3. and $\sum_{n=1}^{\infty} \frac{n^{n-2}}{e^n n!}$.

Proof. (1) We have

$$\frac{1}{(\ln n)^p} > \frac{1}{n}$$

for n large, so the sum diverges by comparison to the harmonic series.

(2) Note that

$$\ln(n!) = \sum_{k=1}^n \ln k > \frac{n \ln 2}{2},$$

so we have

$$\frac{\ln(n!)}{n^p} > \frac{\ln 2}{2} \frac{1}{n^{p-1}}.$$

By comparing to the p -series, we see that the series diverges when $p \leq 2$. Also we have

$$\frac{\ln(n!)}{n^p} < \frac{n \ln n}{n^p} = \frac{\ln n}{n^{p-1}},$$

so when $p > 2$, we get convergence.

(3) Let $a_n = n^{n-2}/(e^n n!)$. Recall that $(1 + 1/n)^n \rightarrow e$ as $n \rightarrow \infty$ and also $(1 + 1/n)^n$ is increasing. Then

$$\frac{a_{n+1}}{a_n} = \frac{(n+1)^{n-1} e^n n!}{e^{n+1} (n+1)! n^{n-2}} = \frac{\left(1 + \frac{1}{n}\right)^{n-2}}{e} = \underbrace{\frac{\left(1 + \frac{1}{n}\right)^n}{e}}_{<1} \left(1 + \frac{1}{n}\right)^{-2} < \left(\frac{n}{n+1}\right)^2 = \frac{\frac{1}{(n+1)^2}}{\frac{1}{n^2}}.$$

Let $b_n = 1/n^2$, then $a_{n+1}/a_n \leq b_{n+1}/b_n$, so by the previous corollary, we see that $\sum_{n=1}^{\infty} a_n$ converges. \square

Theorem 10.2 (Comparison test, third version). *Let $(A) \sim \sum_{n=1}^{\infty} a_n$ and $(B) \sim \sum_{n=1}^{\infty} b_n$ be two positive series and suppose that*

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = \ell > 0.$$

Then (A) converges if and only if (B) converges.

Proof. Let $\epsilon = \ell/2 > 0$. Then there exists N such that when $n \geq N$, we have

$$\frac{\ell}{2} < \frac{a_n}{b_n} < \frac{3\ell}{2} \implies \frac{\ell}{2} b_n < a_n < \frac{3\ell}{2} b_n.$$

Thus (A) converges if and only if (B) converges. \square

Example 10.0.2. Determine the convergence of

1. $\sum_{n=1}^{\infty} \frac{2n^2 + 5n + 1}{\sqrt{n^6 - 3n^2 + 1}},$
2. $\sum_{n=1}^{\infty} \frac{1}{n^{1+\frac{1}{n}}},$
3. and $\sum_{n=1}^{\infty} \left[1 - \sqrt[3]{\frac{n-1}{n+1}} \right]^p$ for $p > 0$.

Proof. (1) Let

$$a_n = \frac{2n^2 + 5n + 1}{\sqrt{n^6 - 3n^2 + 1}} \sim \frac{2n^2}{\sqrt{n^6}} = \frac{2}{n}.$$

Then $a_n/(2/n) \rightarrow 1$ as $n \rightarrow \infty$, so $\sum a_n$ diverges since the harmonic series diverges.

(2) Let

$$a_n = \frac{1}{n^{1+\frac{1}{n}}} \quad \text{and} \quad b_n = \frac{1}{n}.$$

Then $a_n/b_n = 1/(n^{1/n}) \rightarrow 1$ as $n \rightarrow \infty$, so $\sum a_n$ diverges since the harmonic series diverges.

(3) Write

$$\begin{aligned} \sqrt[3]{\frac{n-1}{n+1}} &= \sqrt[3]{\frac{1-\frac{1}{n}}{1+\frac{1}{n}}} = \left(1 - \frac{1}{n}\right)^{1/3} \left(1 + \frac{1}{n}\right)^{-1/3} \\ &= \left(1 - \frac{1}{3n} + o(1/n)\right) \left(1 - \frac{1}{3n} + o(1/n)\right) = 1 - \frac{2}{3n} + o(1/n), \end{aligned}$$

where we made a Taylor expansion. Then we see that

$$a_n \sim \left(\frac{2}{3n}\right)^p,$$

so $\sum a_n$ converges if and only if $p > 1$. □

10.1.2 The Root Test

Theorem 10.3 (Root test). *Let $\sum_{n=1}^{\infty} a_n$ be a positive series and suppose that*

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

Then

1. *if $\ell < 1$, then $\sum_{n=1}^{\infty} a_n$ converges,*
2. *and if $\ell > 1$, then $\sum_{n=1}^{\infty} a_n$ diverges.*

Proof. (1) When $\ell < 1$, then there exists q with $\ell < q < 1$ and N such that when $n \geq N$, $\sqrt[n]{a_n} < q$. Then $a_n < q^n$, so $\sum a_n$ converges by comparing to the geometric series.

(2) When $\ell > 1$, there exists $\ell > q > 1$ and a subsequence $\{n_k\}$ such that $(a_{n_k})^{1/n_k} > q$. This implies that $a_{n_k} > q^{n_k}$, so $a_{n_k} \rightarrow \infty$ as $n_k \rightarrow \infty$. Thus $\sum a_n$ diverges since we do not have $a_n \rightarrow 0$. □

Example 10.0.3. Determine the convergence of

1. $\sum_{n=1}^{\infty} \left[1 + \frac{1}{\sqrt{n}} \right]^{-n^{3/2}},$
2. and $\sum_{n=1}^{\infty} \left(\frac{3n}{n+5} \right)^n \left(\frac{n+2}{n+3} \right)^{n^2}.$

Proof. (1) Let a_n be the n th term in the sum and we see that

$$\sqrt[n]{a_n} = \left[1 + \frac{1}{\sqrt{n}} \right]^{-\sqrt{n}}.$$

Since $\sqrt{n} \rightarrow \infty$ as $n \rightarrow \infty$, we may replace \sqrt{n} with n to see that $\sqrt[n]{a_n} \rightarrow 1/e < 1$, so $\sum a_n$ converges.

(2) Let

$$\sqrt[n]{a_n} = \frac{3n}{n+5} \left(\frac{n+2}{n+3} \right)^n.$$

For the second term, we see that

$$\left(\frac{n+2}{n+3} \right)^n = \left(\frac{1+2/n}{1+3/n} \right)^n \longrightarrow \frac{e^2}{e^3} = \frac{1}{e}$$

as $n \rightarrow \infty$. Then $\sqrt[n]{a_n} \rightarrow 3/e > 1$, so $\sum a_n$ diverges. □

Remark. In the above, we used the fact that

$$\lim_{n \rightarrow \infty} \left(1 + \frac{a}{n} \right)^{bn} = e^{ab}.$$

Lecture 11

Feb. 15 — Absolute Convergence

11.1 Example of the Root Test

Example 11.0.1. Determine the converge of the series

$$\sum_{n=1}^{\infty} \frac{n!}{n^{\sqrt{n}}}.$$

Proof. By Stirling's formula,

$$n! \sim \left(\frac{n}{e}\right)^n \sqrt{2\pi n},$$

in the sense that their ratio tends to 1 as $n \rightarrow \infty$. Then

$$\sqrt[n]{a_n} \sim \frac{n}{e} (2\pi)^{1/2n} n^{1/2n-1/\sqrt{n}},$$

Note that $(2\pi)^{1/2n} \rightarrow 1$ as $n \rightarrow \infty$ since 2π is a constant, and

$$\ln(n^{1/2n-1/\sqrt{n}}) = \left(\frac{1}{2n} - \frac{1}{\sqrt{n}}\right) \ln n = \frac{\ln n}{\frac{1}{1/2n-1/\sqrt{n}}} = \frac{\ln n}{2n/\sqrt{1-2\sqrt{n}}} \sim \frac{\ln n}{2n} = \frac{1/n}{2} \rightarrow 0$$

by L'Hôpital's rule, so $n^{1/2n-1/\sqrt{n}} \rightarrow 1$ as $n \rightarrow \infty$. Then $\sqrt[n]{a_n} \sim n/e \gg 1$, so this series diverges. \square

11.2 The Integral Test

Theorem 11.1 (Integral test). *Let $\{a_n\}$ be a positive decreasing sequence. If there exists a continuous decreasing $f(x)$ on $[1, \infty)$ such that $a_n = f(n)$, then*

$$\sum_{n=1}^{\infty} a_n \text{ converges if and only if } \int_1^{\infty} f(x) dx \text{ converges.}$$

Proof. (\Leftarrow) Suppose that

$$\int_1^{\infty} f(x) dx.$$

converges, i.e. the limit

$$\lim_{A \rightarrow \infty} \int_1^A f(x) dx$$

exists. Then

$$a_k = f(k) = f(k)[k - (k-1)] \leq \int_{k-1}^k f(x) dx$$

since f is decreasing. So

$$\sum_{k=2}^n a_k \leq \sum_{k=2}^n \int_{k-1}^k f(x) dx = \int_1^n f(x) dx.$$

Since the integral converges as $n \rightarrow \infty$, the partial sums of $\sum_{n=1}^{\infty} a_n$ are bounded, so $\sum_{n=1}^{\infty} a_n$ converges by the monotone convergence theorem since $a_n \geq 0$.

(\Rightarrow) Suppose

$$\sum_{n=1}^{\infty} a_n$$

converges. Then

$$a_k = f(k)[(k+1) - k] \geq \int_k^{k+1} f(x) dx$$

since f is decreasing. So

$$\sum_{k=1}^n a_k \geq \sum_{k=1}^n \int_k^{k+1} f(x) dx = \int_1^{n+1} f(x) dx.$$

Since the sum converges as $n \rightarrow \infty$, the integral is bounded and thus converges as $f(x) \geq 0$. \square

Example 11.0.2. For $p > 1$, show that

$$\sum_{n=1}^{\infty} \frac{1}{n^p}$$

converges if and only if $p > 1$.

Proof. Let $a_n = 1/n^p$ and choose

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

for $x > 0$ and note that $f(n) = a_n$. Then look at the integral

$$\int_1^{\infty} \frac{1}{x^p} dx,$$

where we can appeal to integration rules to see that this integral converges if and only if $p > 1$. \square

Example 11.0.3. Show that

$$\sum_{n=2}^{\infty} \frac{1}{n(\ln n)^p}$$

converges if and only if $p > 1$.

Proof. Look at

$$\int_2^{\infty} \frac{1}{x(\ln x)^p} dx = \left[\frac{1}{-p+1} (\ln x)^{-p+1} \right]_{x=2}^{x=\infty},$$

which converges if and only if $p > 1$. \square

Example 11.0.4. Suppose $a_n > 0$ and let $S_n = \sum_{k=1}^n a_k$. Then

1. $\sum_{n=1}^{\infty} \frac{a_{n+1}}{S_n \ln S_n}$ diverges if $\sum_{n=1}^{\infty} a_n$ diverges,
2. and $\sum_{n=1}^{\infty} \frac{a_{n+1}}{S_n (\ln S_n)^2}$ converges if $\sum_{n=1}^{\infty} a_n$ converges.

Proof. (1) Notice $a_n = S_n - S_{n-1} > 0$, so

$$\frac{a_{n+1}}{S_n \ln S_n} = \frac{S_{n+1} - S_n}{S_n \ln S_n} \geq \int_{S_n}^{S_{n+1}} \frac{1}{x \ln x} dx = \ln(\ln S_{n+1}) - \ln(\ln S_n).$$

So we see that

$$\sum_{k=1}^n \frac{a_{k+1}}{S_k \ln S_k} \geq \ln(\ln S_{n+1}) - \ln(\ln a_1)$$

since the sum telescopes. But $\ln(\ln S_{n+1}) \rightarrow \infty$ as $n \rightarrow \infty$, so this sum diverges.

The proof for (2) is left as an exercise, but the idea is similar. □

Remark. If $a_n = 1$, then $S_n = n$ for all n , which implies that

$$\sum_{n=1}^{\infty} \frac{1}{n \ln n} \text{ diverges} \quad \text{and} \quad \sum_{n=1}^{\infty} \frac{1}{n (\ln n)^2} \text{ converges,}$$

which matches the previous example.

Example 11.0.5. Let $f(x_0)$ be positive and decreasing on $[0, \infty)$. Then

$$(A) = \int_a^{\infty} f(x) dx \text{ converges} \quad \text{if and only if} \quad (B) = \int_a^{\infty} f(x) \sin^2 x dx \text{ converges.}$$

Proof. (\Rightarrow) This direction is obvious since $0 \leq f(x) \sin^2 x \leq f(x)$ at every point.

(\Leftarrow) Suppose otherwise that (A) diverges. Then

$$\infty = \int_a^{\infty} f(x) dx = \sum_{n=0}^{\infty} \int_{a+n\pi}^{a+(n+1)\pi} f(x) dx \leq \pi \sum_{n=0}^{\infty} f(a+n\pi)$$

since f is decreasing. This implies that $\sum_{n=0}^{\infty} f(a+n\pi)$ diverges. But then

$$\int_a^{\infty} f(x) \sin^2 x dx \geq \sum_{n=0}^{\infty} f(a+(n+1)\pi) \int_{a+n\pi}^{a+(n+1)\pi} \sin^2 x dx = \frac{\pi}{2} \sum_{n=0}^{\infty} f(a+(n+1)\pi),$$

so we see that

$$\int_a^{\infty} f(x) \sin^2 x dx$$

diverges since $\sum_{n=1}^{\infty} f(a+n\pi)$ diverges. Contradiction. □

11.3 Absolute and Conditional Convergence

Definition 11.1. For a series $(A) = \sum_{n=1}^{\infty} a_n$, if $\sum_{n=1}^{\infty} |a_n|$ converges, then we say that (A) *converges absolutely*. If (A) converges but $\sum_{n=1}^{\infty} |a_n|$ diverges, then we say that (A) *converges conditionally*.

Example 11.1.1. The series

$$\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{n} = 1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \dots$$

converges conditionally. This is because the series itself converges by the alternating series test (which we will see later), but taking absolute values gives the harmonic series, which diverges.

Example 11.1.2. For $p > 1$, the series

$$\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{n^p}$$

converges absolutely. Unlike before, taking absolute values gives a p -series, which converges for $p > 1$.

Definition 11.2. For any $a_n \in \mathbb{R}$, define the *positive* and *negative parts* of a_n by

$$a_n^+ = \begin{cases} a_n & \text{if } a_n \geq 0, \\ 0 & \text{if } a_n < 0, \end{cases} \quad \text{and} \quad a_n^- = \begin{cases} -a_n & \text{if } a_n \leq 0, \\ 0 & \text{if } a_n > 0. \end{cases}$$

Note that $a_n^+, a_n^- \geq 0$ and in particular, $a_n = a_n^+ - a_n^-$ and $|a_n| = a_n^+ + a_n^-$.

Theorem 11.2. Suppose $\sum_{n=1}^{\infty} a_n$ converges absolutely. Then

1. $\sum_{n=1}^{\infty} a_n^+$ and $\sum_{n=1}^{\infty} a_n^-$ converge absolutely,
2. and $|\sum_{n=1}^{\infty} a_n| \leq \sum_{n=1}^{\infty} |a_n|$.

Proof. (1) Write

$$\sum_{n=1}^{\infty} |a_n| = \sum_{n=1}^{\infty} (a_n^+ + a_n^-).$$

Since $a_n^+, a_n^- \geq 0$, this implies that $\sum_{n=1}^{\infty} a_n^+$ and $\sum_{n=1}^{\infty} a_n^-$ converge since they are bounded.

(2) Note that

$$\left| \sum_{k=1}^n a_k \right| \leq \sum_{k=1}^n |a_k|$$

in the finite case. Then let $n \rightarrow \infty$ to get

$$\left| \sum_{k=1}^{\infty} a_k \right| \leq \sum_{k=1}^{\infty} |a_k|,$$

which is the desired result. □

Example 11.2.1. Does the series

$$\sum_{n=1}^{\infty} \left[\frac{\cos n}{\sqrt[3]{n^2}} - \sin \left(\frac{\cos n}{\sqrt[3]{n^2}} \right) \right]$$

converge absolutely?

Proof. Let

$$a_n = \frac{\cos n}{\sqrt[3]{n^2}} - \sin\left(\frac{\cos n}{\sqrt[3]{n^2}}\right)$$

and Taylor expand to get

$$a_n = \frac{\cos n}{\sqrt[3]{n^2}} - \left(\frac{\cos n}{\sqrt[3]{n^2}} + O(1/n^2)\right) = O(1/n^2).$$

Since $\sum_{n=1}^{\infty} 1/n^2$ converges, we see that $\sum_{n=1}^{\infty} a_n$ converges absolutely. \square

11.3.1 The Alternating Series Test

Definition 11.3. A series of the form

$$\sum_{n=1}^{\infty} (-1)^n a_n = a_1 - a_2 + a_3 - a_4 + \dots$$

where $a_n > 0$ is called an *alternating series*.

Theorem 11.3 (Leibniz test). *Suppose $\{a_n\}_{n=1}^{\infty}$ is a decreasing sequence and $\lim_{n \rightarrow \infty} a_n = 0$. Then the infinite series $\sum_{n=1}^{\infty} (-1)^{n+1} a_n$ converges.*

Proof. Let

$$S_n = \sum_{k=1}^n (-1)^{k+1} a_k.$$

Then we have

$$S_{2n} = (a_1 - a_2) + (a_3 - a_4) + \dots + (a_{2n-1} - a_{2n}) \geq S_{2n-2} \geq 0$$

and also that

$$S_{2n} = a_1 - (a_2 - a_3) - (a_4 - a_5) - \dots - (a_{2n-2} - a_{2n-1}) - a_{2n} \leq a_1$$

since $\{a_n\}$ is decreasing. In particular, S_{2n} is bounded and increasing, so

$$S = \lim_{n \rightarrow \infty} S_{2n}$$

exists by the monotone convergence theorem. Now observe that

$$S_{2n+1} = S_{2n} + a_{2n+1},$$

so taking $n \rightarrow \infty$ gives $S_{2n+1} \rightarrow S$ since $S_{2n} \rightarrow S$ and $a_{2n+1} \rightarrow 0$. Thus $\lim_{n \rightarrow \infty} S_n = S$. \square

Remark. This shows that the series

$$\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{n}$$

from earlier indeed converges.

Remark. The proof also gives an error estimate for an alternating series. We have

$$|S_n - S| \leq a_{n+1}$$

since $|S_n - S| = a_{n+1} - (a_{n+2} - a_{n+3}) + \dots \leq a_{n+1}$. We get this since the tail is still an alternating series, and an alternating series is bounded by its first term, as shown in the proof.

Lecture 12

Feb. 20 — Series of Functions

12.1 Rearrangements of Series

Definition 12.1. Let $\sigma : \mathbb{N} \rightarrow \mathbb{N}$ be a bijection, i.e. it is one-to-one and onto. Given an infinite series $\sum_{n=1}^{\infty} a_n$, we define the *rearranged series* to be $\sum_{n=1}^{\infty} a_{\sigma(n)}$.

Theorem 12.1 (Dirichlet). *If $(A) = \sum_{n=1}^{\infty} a_n$ converges absolutely and $(B) = \sum_{n=1}^{\infty} a_{\sigma(n)}$ is any rearrangement of (A) , then (B) also converges and*

$$\sum_{n=1}^{\infty} a_{\sigma(n)} = \sum_{n=1}^{\infty} a_n.$$

Proof. First assume $a_n \geq 0$ and let $S = \sum_{n=1}^{\infty} a_n$ with partial sums $S_n = \sum_{k=1}^n a_k$. Let σ_n be the partial sums of (B) . Then

$$\sigma_m \leq \sum_{n=1}^{\infty} a_n = S \quad (*)$$

since $a_n \geq 0$. Then σ_m is bounded, so (B) converges by the monotone convergence theorem. Also by $(*)$, we can take $m \rightarrow \infty$ to get

$$\lim_{m \rightarrow \infty} \sigma_m \leq S \implies \sum_{n=1}^{\infty} a_{\sigma(n)} \leq S.$$

We also get the reverse inequality by thinking of (A) as a rearrangement of (B) , so the two are equal.

Now for the general case, suppose that $\sum_{n=1}^{\infty} a_n$ is a series with differing signs. Let $a_n^+, a_n^- \geq 0$ be the positive and negative parts of a_n , respectively, so that $|a_n| = a_n^+ + a_n^-$. Now $b_n = a_{\sigma(n)}^+$, and $|b_n| = b_n^+ + b_n^-$, so $b_n^{\pm} = a_{\sigma(n)}^{\pm}$. By the previous part, $\sum_{n=1}^{\infty} b_n^{\pm}$ converges and

$$\sum_{n=1}^{\infty} b_n^{\pm} = \sum_{n=1}^{\infty} a_n^{\pm}.$$

Then we have

$$\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} (b_n^+ - b_n^-) = \sum_{n=1}^{\infty} (a_n^+ - a_n^-) = \sum_{n=1}^{\infty} a_n,$$

which is the desired conclusion. \square

Theorem 12.2 (Riemann). *If $(A) = \sum_{n=1}^{\infty} a_n$ converges conditionally, then there exists a rearrangement $(B) = \sum_{n=1}^{\infty} a_{\sigma(n)}$ such that any one of the following occurs:*

1. (B) converges to any number σ ,
2. (B) diverges to ∞ ,
3. (B) diverges to $-\infty$,
4. (B) oscillates in an unbounded manner,
5. or (B) oscillates in a bounded manner.

Proof. Look this up. □

Remark. This shows that when a series only converges conditionally, then pretty much anything can happen when rearranging, which is not the case for absolutely convergent series.

12.2 Series of Functions

Definition 12.2. A *series of functions* is a series of the form $\sum_{n=1}^{\infty} f_n(x)$, where each $f_n(x)$ is defined on an interval I . Define its *partial sums* to be $S_n(x) = \sum_{k=1}^n f_k(x)$. We say that

$$\sum_{n=1}^{\infty} f_n(x) = S(x),$$

i.e. the series *converges* to $S(x)$, if $\lim_{n \rightarrow \infty} S_n(x) = S(x)$, which can be *pointwise* or *uniform*.

Theorem 12.3 (Cauchy criterion for uniform convergence). *A series $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly on I if and only if for every $\epsilon > 0$, there exists N such that whenever $n \geq N$, for any $x \in I$ and integer p we have*

$$\left| \sum_{k=n+1}^{n+p} f_k(x) \right| < \epsilon.$$

Proof. This is because $\{S_n(x)\}$ is a Cauchy sequence, so for any $\epsilon > 0$, there exists N such that when $n \geq N$,

$$\sup_{x \in I} |S_{n+p}(x) - S_n(x)| < \epsilon,$$

which is precisely the given condition. □

Corollary 12.3.1. *If $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly on I , then $f_n(x)$ converges uniformly to 0 on I .*

Corollary 12.3.2. *Let $f_n(x) \in C([a, b])$. If $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly on (a, b) , then it converges uniformly on $[a, b]$.*

Proof. Since $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly, for any $\epsilon > 0$ there exists N such that when $n \geq N$, we have

$$\left| \sum_{k=n+1}^{n+p} f_k(x) \right| < \epsilon$$

for all $x \in (a, b)$. Let $x \rightarrow a^+$ and $x \rightarrow b^-$ to get

$$\left| \sum_{k=n+1}^{n+p} f_k(a) \right| \leq \epsilon \quad \text{and} \quad \left| \sum_{k=n+1}^{n+p} f_k(b) \right| \leq \epsilon.$$

So for all $x \in [a, b]$, we have

$$\left| \sum_{k=n+1}^{n+p} f_k(x) \right| \leq \epsilon,$$

which gives uniform convergence on $[a, b]$. □

Example 12.2.1. The series

$$\sum_{n=1}^{\infty} \frac{1}{n^x}$$

does not converge uniformly on $(1, \infty)$.

Proof. Note that each $1/n^x$ is continuous but at $x = 1$, the series becomes the harmonic series $\sum_{n=1}^{\infty} 1/n$, which diverges. So by the previous corollary, this series cannot converge uniformly on $(1, \infty)$. □

Theorem 12.4 (Weierstrass M -test). *If there exists a nonnegative and convergent series $\sum_{n=1}^{\infty} M_n$ such that for all $x \in I$, we have*

$$|f_n(x)| \leq M_n,$$

then $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly on I .

Proof. Since $\sum_{n=1}^{\infty} M_n$ converges uniformly, for any $\epsilon > 0$ there exists N such that

$$\left| \sum_{k=n+1}^{n+p} M_k \right| < \epsilon.$$

This directly implies

$$\left| \sum_{k=n+1}^{n+p} f_k(x) \right| \leq \sum_{k=n+1}^{n+p} |f_k(x)| < \epsilon$$

since each M_k is nonnegative. Then $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly on I by the Cauchy criterion. □

Example 12.2.2. If $\sum_{n=1}^{\infty} a_n$ converges absolutely, then

$$\sum_{n=1}^{\infty} \frac{a_n x^n}{1 + x^{2n}}$$

converges uniformly on $(-\infty, \infty)$.

Proof. This is because

$$\left| \frac{a_n x^n}{1 + x^{2n}} \right| \leq |a_n| \underbrace{\frac{|x|^n}{1 + |x|^{2n}}}_{\leq 1} \leq |a_n|,$$

so by the Weierstrass M -test, we get uniform convergence on $(-\infty, \infty)$. □

12.3 Exchange of the Limit and Infinite Series

Theorem 12.5. Let $f_n \in \mathcal{R}([a, b])$ for each $n = 1, 2, \dots$. If $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly to $S(x)$ on $[a, b]$, then $S(x) \in \mathcal{R}([a, b])$ and

$$\sum_{n=1}^{\infty} \int_a^b f_n(x) dx = \int_a^b S(x) dx = \int_a^b \sum_{n=1}^{\infty} f_n(x) dx.$$

Proof. Let $S_n(x) = \sum_{k=1}^n f_k(x)$. Then $S_n \rightarrow S$ uniformly on $[a, b]$, so we can apply Theorem 9.1 to get $S(x) \in \mathcal{R}([a, b])$ and

$$\sum_{n=1}^{\infty} \int_a^b f_n(x) dx = \lim_{n \rightarrow \infty} \int_a^b S_n(x) dx = \int_a^b S(x) dx,$$

which is the desired conclusion.¹ □

Theorem 12.6. Let $f_n(x)$ be continuously differentiable on $[a, b]$. Suppose that

$$\sum_{n=1}^{\infty} f_n(x) = S(x)$$

pointwise on $[a, b]$, and $\sum_{n=1}^{\infty} f'_n(x)$ converges uniformly to $G(x)$ on $[a, b]$. Then $\sum_{n=1}^{\infty} f_n(x)$ converges uniformly to $S(x)$ and $S'(x) = G(x)$. In other words, in this case we have

$$\left(\sum_{n=1}^{\infty} f_n(x) \right)' = \sum_{n=1}^{\infty} f'_n(x).$$

Proof. Similarly apply Theorem 9.2, our previous theorem on exchanging the limit and the derivative. □

Example 12.2.3. Show that

$$S(x) = \sum_{n=1}^{\infty} \frac{\sin nx}{n^3}$$

is continuously differentiable on $(-\infty, \infty)$.

Proof. For each fixed n , we see that $(\sin nx)/n^3$ is continuously differentiable, and we at least have pointwise convergence since

$$\left| \frac{\sin nx}{n^3} \right| \leq \frac{1}{n^3}.$$

Now the series of derivatives

$$\sum_{n=1}^{\infty} \frac{n \cos nx}{n^3} = \sum_{n=1}^{\infty} \frac{\cos nx}{n^2}$$

converges uniformly on $(-\infty, \infty)$ by the Weierstrass M -test since

$$\left| \frac{\cos nx}{n^2} \right| \leq \frac{1}{n^2}.$$

So we can apply the previous theorem to see that S is continuously differentiable on $(-\infty, \infty)$. □

¹This is just applying the previous theorem on exchanging the limit and the integral.

Remark. Changing the n^3 to n^2 in the previous example will cause this argument to fail, since we get

$$\left| \frac{\cos nx}{n} \right| \leq \frac{1}{n},$$

which does not converge. So we cannot use the Weierstrass M -test.

Example 12.2.4. Let

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

Study its differentiability on $(-\infty, \infty)$.

Proof. Observe that

$$\frac{|x|}{n^2 + x^2} \leq \frac{|x|}{n^2},$$

so the series converges pointwise on $(-\infty, \infty)$. Now let $f_n(x) = |x|/(n^2 + x^2)$, and we see that

$$\sum_{n=1}^{\infty} f'_n(x) = \sum_{n=1}^{\infty} \frac{\frac{(n^2+x^2)|x|}{x} - 2x|x|}{(n^2 + x^2)^2} = \sum_{n=1}^{\infty} \frac{\frac{n^2|x|}{x} - x|x|}{(n^2 + x^2)^2}$$

for any $0 < |x| < A$. Now

$$\left| \frac{n^2|x|}{x} - x|x| \right| \leq n^2 + A^2,$$

so $\sum_{n=1}^{\infty} f'_n(x)$ converges uniformly for any x away from 0. So $S(x)$ is differentiable when $x \neq 0$. At $x = 0$, we use the definition of the derivative to see that

$$\lim_{\Delta x \rightarrow 0} \frac{S(\Delta x) - S(0)}{\Delta x} = \lim_{\Delta x \rightarrow 0} \frac{|\Delta x|}{\Delta x} \sum_{n=1}^{\infty} \frac{1}{n^2 + (\Delta x)^2}.$$

From this we get

$$S'_-(0) = -\sum_{n=1}^{\infty} \frac{1}{n^2} \neq \sum_{n=1}^{\infty} \frac{1}{n^2} = S'_+(0),$$

so $S(x)$ is not differentiable at $x = 0$. □

Lecture 13

Feb. 22 — Power Series

13.1 Power Series

Definition 13.1. Given a point x_0 , a *power series* around x_0 is a series of the form

$$\sum_{n=0}^{\infty} a_n(x - x_0)^n = a_0 + a_1(x - x_0) + a_2(x - x_0)^2 + \dots$$

Remark. The question is: For what x does the series converge?

Example 13.1.1. Consider the series¹

$$\sum_{n=0}^{\infty} \frac{x^n}{n!}.$$

In fact this series converges for all $x \in \mathbb{R}$. Let $a_n = x^n/n!$. By the ratio test, for $x \neq 0$, we have

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n \rightarrow \infty} \frac{|x|}{n+1} = 0,$$

so the series converges at $x \neq 0$. Of course, if $x = 0$, then every term past $n = 0$ is zero, so the series also converges there. Thus the series converges everywhere on \mathbb{R} .

Example 13.1.2. The series

$$\sum_{n=0}^{\infty} n!x^n$$

converges only at $x = 0$. For $x \neq 0$, we can similarly apply the ratio test to find that

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n \rightarrow \infty} |n+1||x| = \infty,$$

so the series diverges for $x \neq 0$.

Example 13.1.3. Recall that the geometric series

$$\sum_{n=0}^{\infty} x^n$$

converges if and only if $|x| < 1$.

¹Later we will see that this is the Taylor series for the exponential function e^x .

13.2 Radius of Convergence

Lemma 13.1. *We have the following:*

1. If $(A) = \sum_{n=0}^{\infty} a_n x^n$ converges at $x = x_1 \neq 0$, then it converges absolutely for all x with $|x| < |x_1|$.
2. If (A) diverges at $x = x_2 \neq 0$, then it diverges for all x with $|x| > |x_2|$.

Proof. (1) If $\sum_{n=0}^{\infty} a_n x_1^n$ converges, then $a_n x_1^n \rightarrow 0$ as $n \rightarrow \infty$. In particular, the terms are bounded, so there exists $M > 0$ such that $|a_n x_1^n| \leq M$ for every $n \in \mathbb{N}$. For any $|x| < |x_1|$, let

$$q = \left| \frac{x}{x_1} \right| < 1.$$

Then we have

$$|a_n x^n| = \left| a_n x_1^n \left(\frac{x}{x_1} \right)^n \right| \leq M q^n.$$

Comparing with the geometric series, we get that $\sum_{n=0}^{\infty} a_n x^n$ converges absolutely when $|x| < |x_1|$.

(2) Suppose otherwise that there exists x_3 such that $|x_3| > |x_2|$ and $\sum_{n=0}^{\infty} a_n x_3^n$ converges. Then by (1), we see that the power series converges at $x = x_2$. Contradiction. \square

Corollary 13.0.1. *If $(A) = \sum_{n=0}^{\infty} a_n x^n$ converges at some $x_1 \neq 0$ and diverges at $x_2 \neq 0$, then there exists $R > 0$ such that (A) converges for $|x| < R$ and diverges for $|x| > R$.*

Proof. Let E be the set of all convergence points of (A) . By Lemma 13.1, we have $E \subseteq \{|x| \leq |x_2|\}$ since (A) diverges for all $|x| > |x_2|$. Let

$$R = \sup\{|x| : x \in E\},$$

which exists since E is nonempty and bounded above by $|x_2|$. Also $R > 0$ since $x_1 \in E$ and $x_1 \neq 0$. Now if $|x| < R$, then there exists $x_1 \in E$ such that $|x| < |x_1| < R$ and $x = x_1$ is a convergence point.² By Lemma 13.1, we get that (A) converges at x . If $|x| > R$, then there exists x_2 such that $|x| > |x_2| > R$ and (A) diverges at $x = x_2$. Then by Lemma 13.1, (A) diverges at x . \square

Remark. The R in Corollary 13.0.1 is called the *radius of convergence* of the power series. If $(A) = \sum_{n=0}^{\infty} a_n x^n$ converges for all $x \in \mathbb{R}$, then by convention we use $R = \infty$. If (A) converges only at $x = 0$, we use $R = 0$. At $x = \pm R$, the convergence or divergence of (A) needs to be checked separately.

Theorem 13.1. *For a power series $\sum_{n=0}^{\infty} a_n x^n$, let*

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

Then

1. if $\rho = 0$, then $R = \infty$,
2. if $\rho = \infty$, then $R = 0$,
3. and if $\rho \in (0, \infty)$, then $R = 1/\rho$.

²This is by definition of the supremum.

Proof. We use the root test for $\sum_{n=0}^{\infty} |a_n x^n|$. Let $A_n = |a_n x^n|$. Then

$$\limsup_{n \rightarrow \infty} \sqrt[n]{A_n} = \limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|} \cdot |x| = \rho |x|.$$

First suppose $0 < \rho < \infty$. Then $\sum_{n=0}^{\infty} |a_n x^n|$ converges if $|x|\rho < 1$ and diverges if $|x|\rho > 1$. This gives $R = 1/\rho$. Now if $\rho = 0$, then

$$\limsup_{n \rightarrow \infty} \sqrt[n]{A_n} = 0 < 1,$$

so $\sum_{n=0}^{\infty} |a_n x^n|$ regardless of the choice of x , i.e. $R = \infty$. Finally if $\rho = \infty$, then for $x_0 \neq 0$,

$$\limsup_{n \rightarrow \infty} \sqrt[n]{A_n} = \infty > 1.$$

By the root test, this implies that $\sum_{n=0}^{\infty} |a_n x^n|$ diverges for all $x \neq 0$, i.e. $R = 0$. □

Corollary 13.1.1. For $\sum_{n=0}^{\infty} a_n x^n$ with $a_n \neq 0$, if

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| = \rho,$$

then the radius of convergence is $R = 1/\rho$.

Proof. Left as an exercise. □

Example 13.1.4. Find the convergence intervals for

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

Proof. (1) Let a_n be the summand. Then

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n \rightarrow \infty} \frac{2n \ln^2(n+1)}{(n+1) \ln^2(n+2)} = 2,$$

so $R = 1/2$. So we get convergence for $|x+1| < 1/2$, i.e. $x \in (-3/2, -1/2)$. At $x = -3/2, -1/2$, we get

$$\sum_{n=1}^{\infty} \frac{1}{n \ln^2(n+1)}$$

after taking absolute values, which converges by the integral test. So the interval is $[-3/2, -1/2]$.

(2) Let the general term be

$$a_k = \begin{cases} n^n & \text{if } k = n^2 \text{ for some } n \in \mathbb{N}, \\ 0 & \text{otherwise.} \end{cases}$$

Then we see that

$$\limsup_{k \rightarrow \infty} \sqrt[k]{|a_k|} = \lim_{n \rightarrow \infty} \sqrt[n^2]{n^n} = \lim_{n \rightarrow \infty} \sqrt[n]{n} = 1,$$

so $R = 1$. At $x = \pm 1$, the series diverges since the general term $n^n x^{n^2}$ does not go to 0 when $|x| = 1$. So we conclude that the interval of convergence is $(-1, 1)$. □

Theorem 13.2. If $(A) = \sum_{n=0}^{\infty} a_n x^n$ has radius of convergence $R > 0$ (including $R = \infty$), then for any $0 < r < R$, the power series (A) converges uniformly on $[-r, r]$. Moreover, if (A) converges at $x = R < \infty$ (or $x = -R$), then (A) converges uniformly on $[0, R]$ (or $[-R, 0]$).

Proof. For $x \in [-r, r]$, we have $|a_n x^n| \leq |a_n| r^n$, and $\sum_{n=0}^{\infty} |a_n| r^n$ converges since $r < R$. So by the Weierstrass M -test, we get uniform convergence on $[-r, r]$. Second part left as an exercise. \square

Corollary 13.2.1. For a power series $(A) = \sum_{n=0}^{\infty} a_n x^n$, we have the following:

1. if (A) has radius of convergence $R > 0$, then $f(x) = \sum_{n=0}^{\infty} a_n x^n$ is continuous on $(-R, R)$,
2. $f(x)$ is differentiable on $(-R, R)$,
3. and $f(x) \in C^\infty(-R, R)$, i.e. it is infinitely differentiable.

Proof. (1) We get

$$\lim_{x \rightarrow x_0} f(x) = \lim_{x \rightarrow x_0} \sum_{n=0}^{\infty} a_n x^n = \sum_{n=0}^{\infty} \lim_{x \rightarrow x_0} a_n x^n = f(x_0)$$

since we have uniform convergence.

(2) One can verify that $\sum_{n=0}^{\infty} a_n n x^{n-1}$ also has radius of convergence R . In particular, the derivative series also converges uniformly, so by Theorem 9.2, we can differentiate term by term.

(3) We can repeat (2) as many times as we want. \square

Theorem 13.3. Suppose $f(x) = \sum_{n=0}^{\infty} a_n x^n$ has radius of convergence $R > 0$. Then for any $x \in (-R, R)$, we have $f \in \mathcal{R}([0, x])$ and

$$\int_0^x f(t) dt = \int_0^x \sum_{n=0}^{\infty} a_n t^n dt = \sum_{n=0}^{\infty} a_n \int_0^x t^n dt = \sum_{n=0}^{\infty} \frac{a_n}{n+1} x^{n+1}.$$

Proof. As $\sum_{n=0}^{\infty} a_n x^n$ converges uniformly in $[-r, r]$, by Theorem 9.1 we can integrate term by term. \square

Example 13.1.5. Show that

$$\sum_{n=1}^{\infty} \frac{x^n}{n} = -\ln(1-x)$$

for $-1 < x < 1$.

Proof. By the previous theorem, we can write

$$\sum_{n=1}^{\infty} \frac{x^n}{n} = \int_0^x \sum_{n=1}^{\infty} t^{n-1} dt = \int_0^x \frac{1}{1-t} dt = -\ln(1-x),$$

as desired. Note that we used the geometric series in the second step. \square

Example 13.1.6. Find the sum

$$\sum_{n=0}^{\infty} \frac{(-1)^n}{3n+1}.$$

Proof. Let

$$S(x) = \sum_{n=0}^{\infty} \frac{(-1)^n}{3n+1} x^{3n+1}.$$

In particular, $S(1)$ is the desired sum, so S converges at $x = 1$ by the alternating series test. Then

$$\begin{aligned} S(1) &= \sum_{n=0}^{\infty} (-1)^n \int_0^1 x^{3n} dx = \int_0^1 \sum_{n=0}^{\infty} (-x^3)^n dt = \int_0^1 \frac{1}{1+x^3} dx \\ &= \frac{1}{3} \left[\ln \frac{1+x}{\sqrt{1-x+x^2}} + \sqrt{3} \arctan \frac{2x-1}{\sqrt{3}} \right]_{x=0}^{x=1} = \frac{1}{3} \left(\ln 2 + \frac{\pi}{\sqrt{3}} \right) \end{aligned}$$

since we have uniform convergence on $[0, 1]$.

□

Lecture 14

Feb. 27 — Taylor Series

14.1 Taylor Series

Recall from Theorem 13.2.1 that $f(x) = \sum_{n=0}^{\infty} a_n x^n$ is C^∞ on $(-R, R)$, where R is its radius of convergence. Here we can differentiate term by term, i.e. we have

$$\begin{aligned}f(x) &= a_0 + a_1 x + a_2 x^2 + a_3 x^3 \cdots, \\f'(x) &= a_1 + 2a_2 x + 3a_3 x^2 + \cdots, \\f''(x) &= 2a_2 + 6a_3 x + \cdots.\end{aligned}$$

In particular, if we let $x = 0$, then

$$a_0 = f(0), \quad a_1 = f'(0), \quad a_2 = \frac{f''(0)}{2!}, \quad \dots, \quad a_n = \frac{f^{(n)}(0)}{n!}.$$

Here we call

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(0)}{n!} x^n$$

the *Taylor series* of f at 0.

Corollary 14.0.1. *If $f(x)$ has the power series expansion $\sum_{n=0}^{\infty} c_n(x-a)^n$ on an open interval I containing a , then $f \in C^\infty(I)$ and*

$$c_n = \frac{f^{(n)}(a)}{n!}.$$

for all $n \geq 0$. In particular, if f has a power series expansion

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

then c_n is unique.

Remark. Since Taylor series are unique, we may use any way we want to find its coefficients.

Example 14.0.1. Suppose we would like to find the Taylor series of $\ln(1-x)$. It is easier to observe

$$(\ln(1-x))' = \frac{1}{1-x}$$

and find the Taylor series of its derivative to be

$$\frac{1}{1-x} = 1 + x + x^2 + \cdots + x^n + \dots$$

Then we can integrate term by term to find the Taylor series of $\ln(1-x)$.

14.2 Convergence of Taylor Series

Given a function $f \in C^\infty(I)$, do we always have

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(0)}{n!} x^n$$

in the interval I ?

Example 14.0.2. Consider

$$f(x) = \begin{cases} e^{-1/x^2} & \text{if } x \neq 0, \\ 0 & \text{if } x = 0. \end{cases}$$

Away from $x = 0$, we have

$$f' = \frac{2}{x^3} e^{-1/x^2}, \quad f'' = e^{-1/x^2} \left[-\frac{6}{x^4} + \frac{4}{x^6} \right], \quad f''' = e^{-1/x^2} P_7(1/x), \quad \dots$$

So f is C^∞ away from $x = 0$. In particular, $f^{(n)}(x) \rightarrow 0$ as $x \rightarrow 0$ for all $n \geq 0$ since

$$\lim_{x \rightarrow 0} \frac{1}{x^m} e^{-1/x^2} = 0$$

for all $m \geq 0$. Now also

$$f'(0) = \lim_{x \rightarrow 0} \frac{e^{-1/x^2}}{x} = 0,$$

so f' is continuous on \mathbb{R} . We can continue this to see that each $f^{(n)}$ is continuous on \mathbb{R} . So $f \in C^\infty(\mathbb{R})$ and $f^{(n)}(0) = 0$ for all $n \geq 0$. Thus its Taylor series is identically zero, but $f(x)$ is not the zero function.

Remark. Recall Lagrange's remainder term for the Taylor polynomial, which says

$$f(x) - \sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} (x - x_0)^k = R_n(x),$$

where

$$R_n(x) = \frac{1}{(n+1)!} f^{(n+1)}(\xi) (x - x_0)^{n+1}$$

and ξ is between x and x_0 . We can use this to justify the convergence of Taylor series.

Theorem 14.1. *Let $R \in (0, \infty)$ and $f \in C^\infty(x_0 - R, x_0 + R)$. If there exists $M > 0$ such that for all $x \in (x_0 - R, x_0 + R)$, we have*

$$|f^{(n)}(x)| \leq M^n$$

for each $n = 1, 2, \dots$, then

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(x_0)}{n!} (x - x_0)^n$$

for all $x \in (x_0 - R, x_0 + R)$.

Proof. By Lagrange's remainder term formula, we have

$$|R_n(x)| = \frac{1}{(n+1)!} |f^{(n+1)}(\xi)| |x - x_0|^{n+1} \leq \frac{1}{(n+1)!} M^{n+1} R^{n+1} = \frac{(MR)^{n+1}}{(n+1)!} \rightarrow 0$$

as $n \rightarrow \infty$ since M, R are fixed. Thus we get the desired equality, since the error term goes to zero. \square

Example 14.0.3. For $f(x) = e^x$, we have $f^{(n)}(x) = e^x$. Then for $x \in (-R, R)$, we have $|f^{(n)}(x)| \leq e^R$. So by the previous theorem, we get

$$e^x = \sum_{n=0}^{\infty} \frac{1}{n!} x^n$$

for all $x \in \mathbb{R}$, since we can take R as large as we would like.

14.3 Metric Spaces

Definition 14.1. We call a pair (X, ρ) a *metric space* if X is nonempty and $\rho : X \times X \rightarrow \mathbb{R}^+$ satisfies:

1. positive-definiteness: $\rho(x, y) \geq 0$ and $\rho(x, y) = 0$ if and only if $x = y$,
2. symmetry: $\rho(x, y) = \rho(y, x)$,
3. and the triangle inequality: $\rho(x, y) \leq \rho(x, z) + \rho(z, y)$ for all $x, y, z \in X$.

We say ρ is a *distance function* if it satisfies the above properties.

Example 14.1.1. For $X = \mathbb{R}^3$, we may take $\rho(\vec{x}, \vec{y}) = \|\vec{x} - \vec{y}\|$.

Example 14.1.2. For $X = C([a, b])$, the set of all continuous functions on $[a, b]$, we can define

$$\rho(x, y) = \max_{t \in [a, b]} |x(t) - y(t)|$$

for any two $x(t), y(t) \in C([a, b])$. This is called the *maximum norm* or the ℓ^∞ norm.

Definition 14.2 (Convergence). We say that $x_n \rightarrow x_0$ in (X, ρ) if $\rho(x_n, x_0) \rightarrow 0$ as $n \rightarrow \infty$. We write

$$\lim_{n \rightarrow \infty} x_n = x_0.$$

Example 14.2.1. If $x_n(t) \in C([a, b])$, then $x_n \rightarrow x_0$ means $x_n(t) \rightarrow x_0(t)$ uniformly in $[a, b]$.¹

Definition 14.3. We say that $\{x_n\}$ is a *Cauchy sequence* in (X, ρ) if $\rho(x_n, x_m) \rightarrow 0$ when $n, m \rightarrow \infty$, i.e. for any $\epsilon > 0$, there exists N such that if $n, m \geq N$, then $\rho(x_n, x_m) < \epsilon$.

Definition 14.4. If every Cauchy sequence in (X, ρ) has a limit $x_n \rightarrow x^*$, then we say that (X, ρ) is a *complete* metric space.

Example 14.4.1. The continuous functions $C([a, b])$ with the maximum norm is complete.

Definition 14.5. Let $(X, \rho), (Y, r)$ be two metric spaces. Then we say $T : X \rightarrow Y$ is *continuous* if for any $\{x_n\}$ and $x_0 \in X$, we have $\rho(x_0, x_n) \rightarrow 0$ implies $r(T(x_0), T(x_n)) \rightarrow 0$.

¹This is if we use the maximum norm from earlier.

Theorem 14.2. *A function $T : (X, \rho) \rightarrow (Y, r)$ is continuous if and only if for all $\epsilon > 0$ and $x_0 \in X$, there exists $\delta = \delta(x_0, \epsilon) > 0$ such that $\rho(x, x_0) < \delta$ implies $r(T(x), T(x_0)) < \epsilon$.*

Proof. Check this as an exercise □

14.4 Existence and Uniqueness Problem for ODEs

Consider the ordinary differential equation (ODE) problem

$$\begin{cases} \frac{dx}{dt} = F(t, x), \\ x(0) = \xi. \end{cases} \quad (1)$$

We would like to show that this ODE has a local solution.² To do this, we can transform the ODE into³

$$x(t) = \xi + \int_0^t f(\tau, x(\tau)) d\tau.$$

Now we would like to find a fixed point of this map. Let $h > 0$ and consider $X = C([-h, h])$ with the maximum norm. Define the mapping $T : X \rightarrow X$ by

$$(Tx)(t) = \xi + \int_0^t f(\tau, x(\tau)) d\tau$$

for any $x \in X$. Then solving (1) is equivalent to finding a point $x \in X$ such that $x = Tx$, i.e. x is a fixed point of T . We can do this via contraction mapping.

14.5 The Contraction Mapping Principle

Definition 14.6. We say $T : (X, \rho) \rightarrow (X, \rho)$ is a *contraction mapping* if there exists $a \in (0, 1)$ such that

$$\rho(Tx, Ty) \leq a\rho(x, y)$$

for any $x, y \in X$.

Example 14.6.1. Let $X = [0, 1]$ and $T(x)$ be differentiable on $[0, 1]$ with $T(x) \in [0, 1]$ and $|T'(x)| \leq a < 1$. Then $T : X \rightarrow X$ is a contraction mapping since

$$\rho(Tx, Ty) = |T(x) - T(y)| = |T'(\xi)(x - y)| \leq a|x - y|$$

by the mean value theorem.

Theorem 14.3 (Contraction mapping principle⁴). *Let (X, ρ) be a complete metric space and $T : X \rightarrow X$ be a contraction mapping. Then T has a unique fixed point on X .*

²The solution may not exist for longer time periods, e.g. it might blow up at some point.

³This process is called *Picard iteration*.

⁴This is also known as the *Banach fixed-point theorem*.

Proof. For any $x_0 \in X$, define a sequence recursively by $x_{n+1} = Tx_n$, i.e. $x_n = T^n x_0$. Now we show that $\{x_n\}$ is a Cauchy sequence. To do this, observe that

$$\rho(x_{n+1}, x_n) = \rho(Tx_n, Tx_{n-1}) \leq a\rho(x_n, x_{n-1}) \leq a^2\rho(x_{n-1}, x_{n-2}) \leq \cdots \leq a^n\rho(x_1, x_0)$$

for some $0 < a < 1$ since ρ is a contraction mapping. So for any integer $p > 0$, by the triangle inequality we have

$$\rho(x_{n+p}, x_n) \leq \sum_{i=1}^p \rho(x_{n+i}, x_{n+i-1}) \leq \sum_{i=0}^{p-1} a^{n+i} \rho(x_0, x_1) \leq \sum_{i=0}^{\infty} a^{n+i} \rho(x_0, x_1) = \frac{a^n}{1-a} \rho(x_0, x_1).$$

Since $\rho(x_0, x_1)$ is fixed and $0 < a < 1$, we see that $\{x_n\}$ is a Cauchy sequence. Since X is complete, we have $x_n \rightarrow x^* \in X$. Now we show that x^* is a fixed point of T . This is because $x_{n+1} = Tx_n$, and letting $n \rightarrow \infty$ gives $x^* = Tx^*$, since T is continuous.⁵ Next, we show that x^* is the only fixed point. To do this, suppose otherwise that x^{**} is also a fixed point. Then

$$\rho(x^*, x^{**}) = \rho(Tx^*, Tx^{**}) \leq a\rho(x^*, x^{**}).$$

Since $0 < a < 1$, we must have $\rho(x^*, x^{**}) = 0$, i.e. $x^* = x^{**}$. □

⁵One can show that any contraction mapping is continuous.