MATH 4318: Analysis II

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Contents

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

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

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 $f : U \to \mathbb{R}$. 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. $\square$

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

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

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

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

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

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

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 $x \to 0$. Thus f is not differentiable at $x = 0$.

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

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

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 $f, g : U \to \mathbb{R}$ 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. □

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 $f : U \to V, g : V \to \mathbb{R}$ 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

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

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

Remark. The rough idea of what we did here is

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

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 $\frac{d}{dx} \ln(x)\big|_{x=h} = 1/h$, 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, $f : I \to \mathbb{R}$ 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 ay $|x - x_0| < \delta$, 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. □

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. □

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. □

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. □

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. □

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 $x_0 \in (a,b)$,

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

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. □

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 $f \to 0$ as $x \to \infty$, 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

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

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

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

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

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

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

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

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

By Lagrange's theorem,

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

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

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

So the left-hand side is precisely

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

By the chain rule, we have

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

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. $\square$

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), $\lim_{x\to a^+} f(x) = \lim_{x\to a^+} g(x) = 0$, and $g'(x) \neq 0$ for any $x \in (a,b)$. Then if $\lim_{x\to a^+} f'(x)/g'(x)$ exists, we have*

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

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

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

as desired. $\square$

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

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

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

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

as desired. □

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

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

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 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 $f(x) \to 0^+$ and $g(x) \to 0^+$ when $x \to x_0$, then $\lim_{x\to x_0} f(x)^{g(x)}$ 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)

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

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

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

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

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

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

3.3 Taylor's Theorem

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

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

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 $f^{(n)}(a)$. □

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

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

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

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 $g'(a) = \cdots = g^{(n)}(a) = 0$. Then by Rolle's theorem (higher order), there exists $\xi \in (a, b)$ such that $g^{(n+1)}(\xi) = 0$. In other words,

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

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 $\xi \in [a, b]$. □

[1] Note 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 $f : [a, b] \to \mathbb{R}$ and $f'(a), \ldots, f^{(n)}(a)$ exist, then if

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

as $x \to a^+$ 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

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

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

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

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

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

We can solve to get

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

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 $x \to 0$ and $g(x) = bx^n + o(x^n)$ where $b \neq 0$. Then

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

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

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

Proof. Note that

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

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

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

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

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

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

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

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

Example 4.0.5. Find

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

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 $f(1) = f(2)$, 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

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

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. $\square$

Lecture 5

Jan. 23 — The Riemann Integral

5.1 The Anti-Derivative

Recall the *anti-derivative* from calculus:

Definition 5.1. Let $f : U \to \mathbb{R}$ where U is an interval in $\mathbb{R}$. If there exists a differentiable function $F : U \to \mathbb{R}$ 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

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

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

Remark. The eventual goal is to show that any continuous function $f : [a, b] \to \mathbb{R}$ 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. $\square$

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 have[1]

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

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 $x_0, x_1, \ldots, x_n$ such that $a = x_0 < x_1 < \cdots < x_n = b$.

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

Definition 5.4. For any partition $x_0, x_1, \ldots, x_n$, 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 $f : [a, b] \to \mathbb{R}$. 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

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

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 $x_0, x_1, \ldots, x_n$,

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

[1] This is the *fundamental theorem of calculus*.

[2] The 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 $f : [a, b] \to \mathbb{R}$ 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 $A = 0$. □

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

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

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 $f : [a, b] \to \mathbb{R}$ 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 $f, g : [a, b] \to \mathbb{R}$ 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 $f : [a, b] \to \mathbb{R}$ 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 $\epsilon \to 0$ gives $A \geq 0$. □

Corollary 5.0.1. *If $f, g : [a, b] \to \mathbb{R}$ 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. $\square$

Corollary 5.0.2. *If $f : [a, b] \to \mathbb{R}$ 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 $f : [a,b] \to \mathbb{R}$ 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 $(a-b)/n$. 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 $\lim_{n\to\infty} S_n = A$. 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. $\square$

Remark. Recall the step function $f : [a,b] \to \mathbb{R}$ 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 $f : [a, b] \to \mathbb{R}$ 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 $f : [a, b] \to \mathbb{R}$ is integrable if and only if for any $\epsilon > 0$, there exist step functions f_1, f_2 such that $f_1(x) \le f(x) \le f_2(x)$ 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 $x_0 < x_1 < \cdots < x_n$ 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

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

Similarly define

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

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 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 $\eta \to 0$ gives the desired result. □

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

Proof. This was shown in the proof of the previous proposition. □

Theorem 6.1. *If $f : [a,b] \to \mathbb{R}$ 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

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

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

6.2 The Fundamental Theorem of Calculus

Theorem 6.2 (Fundamental theorem of calculus)**.** *If $f : [a,b] \to \mathbb{R}$ has anti-derivative $F : [a,b] \to \mathbb{R}$ 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 $x_0 < x_1 < \cdots < x_n$ be a partition of width $< \delta$. Then by telescoping,

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

[1] Here $\mathcal{R}([a,b])$ 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 $\epsilon \to 0$ gives $F(b) - F(a) = A$. $\square$

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,*

$$\int_a^b f(x)\,dx = \int_a^c f(x)\,dx + \int_c^b f(x)\,dx. \tag{$*$}$$

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 $f_1 \le f \le f_2$ and

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

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

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

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 $g_1 \le f \le g_2$ on $[a, c]$, $h_1 \le f \le h_2$ 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 $f_1 \le f \le f_2$ 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 $f : [a,b] \to \mathbb{R}$ is continuous, then*[1]

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

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

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

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

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

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

[1] Note 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 $f : [a, b] \to \mathbb{R}$ 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 $i = 1, 2, \ldots, n$. We will call this the *oscillation amplitude* of f.

Theorem 7.2. *A function $f : [a, b] \to \mathbb{R}$ 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 eixsts $\delta > 0$ such that for any two Riemann sums S_1, S_2 over partitions of with $< \delta$, 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 $\eta \to 0$ gives the desired result. $\square$

Theorem 7.3. *A function $f : [a, b] \to \mathbb{R}$ 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

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

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

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

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

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

This implies

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

Thus

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

so that f is integrable. $\square$

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. □

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

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

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

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

which shows the desired result. □

Corollary 8.1.1. *If $f : [a,b] \to \mathbb{R}$ 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 $m \le f(x) \le M$ 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

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

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

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 $|f|, |g| \le M$. 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

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

because

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

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

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

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*

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

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

$$\big||f(x)| - |f(y)|\big| \le |f(x) - f(y)|,$$

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

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

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

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

This immediately implies the desired result. □

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

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

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 $B^2 \le AC$, which will imply $(*)$ by the previous theorem. Then
$$0 \le \int_a^b (t|f| - |g|)^2\,dx = At^2 - 2Bt + C$$
for any $t \in \mathbb{R}$. So the discriminant must satisfy $(2B)^2 - 4AC \le 0$, which gives $B^2 \le AC$ as desired. □

Example 8.0.4 (Riemann-Lebesgue lemma)**.** If $f \in \mathcal{R}([a,b])$, then
$$\lim_{\lambda\to\infty} \int_a^b f(x)\sin(\lambda x)\,dx = 0.$$

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 $|f| \le M$ on $[a,b]$ since f is integrable. Then we choose
$$\lambda > \frac{4nM}{\epsilon}.$$
We can estimate
$$\begin{aligned}
\left|\int_a^b f(x)\sin(\lambda x)\,dx\right| &= \left|\sum_{i=1}^n \int_{x_{i-1}}^{x_i} (f(x) - f(x_i) + f(x_i))\sin(\lambda x)\,dx\right| \\
&\le \sum_{i=1}^n |f(x_i)| \left|\int_{x_{i-1}}^{x_i} \sin(\lambda x)\,dx\right| + \sum_{i=1}^n \int_{x_{i-1}}^{x_i} \underbrace{|f(x) - f(x_i)|}_{\le \omega_i(f)}\underbrace{|\sin(\lambda x)|}_{\le 1}\,dx \\
&\le M\sum_{i=1}^n \frac{\overbrace{|\cos(\lambda x_i) - \cos(\lambda x_{i-1})|}^{\le 2}}{\lambda} + \sum_{i=1}^n \int_{x_{i-1}}^{x_i} \omega_i(f)\,dx \\
&\le M\frac{2n}{\lambda} + \sum_{i=1}^n \omega_i(f)\Delta x_i < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.
\end{aligned}$$
So as $\lambda \to \infty$, the integral goes to 0. □

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 $f_n \to f$ pointwise, then does

$$\int_a^b f_n \, dx \to \int_a^b f \, dx$$

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

Example 9.0.1. Define

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

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

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

9.2 Exchange of the Limit and Integral

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

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

Proof. Suppose that $f_n \to f$ 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 $f_n \to f$ 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

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

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,

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

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

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

Now note that

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

so we see

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

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 $f_1, \ldots, f_n, \ldots$ 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*

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

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

$$f' = \lim_{n\to\infty} f_n'.$$

Proof. By the fundamental theorem of calculus, we have

$$\int_a^x f_n'(t)\,dt = f_n(x) - f_n(a). \tag{$*$}$$

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

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

Let $\lim_{n\to\infty} f_n(x) = f(x)$, which exists by $(*)$. Then RHS $\to f(x) - f(a)$, 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

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

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

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

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

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

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

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

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

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

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

so $S_m \to \infty$. 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*

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

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

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

This is precisely the desired result. □

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

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

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

diverges. Two 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 $0 \le a_n \le b_n$. 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 $A_n \le B_n$ since $0 \le a_n \le b_n$, so A_n is also bounded above. Now note that A_n is increasing since $a_n \ge 0$, 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 $A_n \le B_n$, so B_n is also unbounded and thus we see that $\sum_{n=1}^{\infty} b_n$ diverges. □

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

- $0 \le a_n \le b_n$ when $n \ge n_0$
- $0 \le a_n \le M b_n$ for some $M > 0$,
- or there exists $0 < d_n < M$ such that $0 \le a_n \le d_n b_n$.

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

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

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

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

which we can extended to $d_n \le \cdots \le d_1$. Then $\{d_n\}$ is a bounded sequence, so $a_n = b_n d_n$, which implies the desired conclusion by the above remark. □

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

Example 10.0.1. Determine the convergence of

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

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 $(1 + 1/n)^n \to e$ as $n \to \infty$ 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*

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

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. $\displaystyle\sum_{n=1}^{\infty} \frac{2n^2+5n+1}{\sqrt{n^6-3n^2+1}}$,
2. $\displaystyle\sum_{n=1}^{\infty} \frac{1}{n^{1+\frac{1}{n}}}$,
3. and $\displaystyle\sum_{n=1}^{\infty} \left[1-\sqrt[3]{\frac{n-1}{n+1}}\right]^p$ 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 $a_n/(2/n) \to 1$ as $n \to \infty$, 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 $a_n/b_n = 1/(n^{1/n}) \to 1$ as $n \to \infty$, 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*

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

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 $a_{n_k} \to \infty$ as $n_k \to \infty$. Thus $\sum a_n$ diverges since we do not have $a_n \to 0$. □

Example 10.0.3. Determine the convergence of

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

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

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

Since $\sqrt{n}\to\infty$ as $n\to\infty$, we may replace $\sqrt{n}$ with n to see that $\sqrt[n]{a_n}\to 1/e<1$, 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 $n\to\infty$. Then $\sqrt[n]{a_n}\to 3/e>1$, so $\sum a_n$ diverges. $\square$

Remark. In the above, we used the fact that

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

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 $n \to \infty$. Then

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

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

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

by L'Hôpital's rule, so $n^{1/2n-1/\sqrt{n}} \to 1$ as $n \to \infty$. 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*

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

Proof. ($\Leftarrow$) Suppose that

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

converges, i.e. the limit

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

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 $n \to \infty$, 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 $n \to \infty$, the integral is bounded and thus converges as $f(x) \geq 0$. □

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 $p > 1$. □

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 $p > 1$. □

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

1. $\displaystyle\sum_{n=1}^{\infty} \frac{a_{n+1}}{S_n \ln S_n}$ diverges if $\displaystyle\sum_{n=1}^{\infty} a_n$ diverges,

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

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

which is the desired result. $\square$

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 $\lim_{n\to\infty} a_n = 0$. 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

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

exists by the monotone convergence theorem. Now observe that

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

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

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 $\sigma : \mathbb{N} \to \mathbb{N}$ 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

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

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

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

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. □

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. $\square$

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 $\lim_{n\to\infty} S_n(x) = S(x)$, 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. $\square$

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 $x \to a^+$ and $x \to b^-$ to get

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

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

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

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*

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

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

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

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

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

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 $n = 1, 2, \ldots$. 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 $S_n \to S$ uniformly on $[a,b]$, so we can apply Theorem 9.1 to get $S(x) \in \mathcal{R}([a,b])$ and

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

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

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

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

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

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

[1] This 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

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

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 $x = 0$. $\square$

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 series[1]

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

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

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

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

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

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 $|x| < 1$.

[1] Later 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 $a_n x_1^n \to 0$ as $n \to \infty$. 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*

$$\limsup_{n \to \infty} \sqrt[n]{|a_n|} = \rho.$$

Then

1. *if* $\rho = 0$*, then* $R = \infty$,
2. *if* $\rho = \infty$*, then* $R = 0$,
3. *and if* $\rho \in (0, \infty)$*, then* $R = 1/\rho$.

[2] This 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

$$\limsup_{n\to\infty} \sqrt[n]{A_n} = \limsup_{n\to\infty} \sqrt[n]{|a_n|} \cdot |x| = \rho|x|.$$

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

$$\limsup_{n\to\infty} \sqrt[n]{A_n} = 0 < 1,$$

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 $x_0 \neq 0$,

$$\limsup_{n\to\infty} \sqrt[n]{A_n} = \infty > 1.$$

By the root test, this implies that $\sum_{n=0}^{\infty} |a_n x^n|$ diverges for all $x \neq 0$, i.e. $R = 0$. $\square$

Corollary 13.1.1. *For $\sum_{n=0}^{\infty} a_n x^n$ with $a_n \neq 0$, if*

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

then the radius of convergence is $R = 1/\rho$.

Proof. Left as an exercise. $\square$

Example 13.1.4. Find the convergence intervals for

1. $\displaystyle\sum_{n=1}^{\infty} \frac{2^n (x+1)^n}{n \ln^2(n+1)}$,
2. and $\displaystyle\sum_{n=1}^{\infty} n^n x^{n^2}$.

Proof. (1) Let a_n be the summand. Then

$$\lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n\to\infty} \frac{2n \ln^2(n+1)}{(n+1)\ln^2(n+2)} = 2,$$

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

$$\limsup_{k\to\infty} \sqrt[k]{|a_k|} = \lim_{n\to\infty} \sqrt[n^2]{n^n} = \lim_{n\to\infty} \sqrt[n]{n} = 1,$$

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 $(-1, 1)$. $\square$

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 $|a_n x^n| \le |a_n| r^n$, 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. □

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

$$\lim_{x \to x_0} f(x) = \lim_{x \to x_0} \sum_{n=0}^{\infty} a_n x^n = \sum_{n=0}^{\infty} \lim_{x \to x_0} a_n x^n = f(x_0)$$

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. □

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. □

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. □

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 $[0, 1]$. $\square$

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

$$a_0 = f(0), \quad a_1 = f'(0), \quad a_2 = \frac{f''(0)}{2!}, \quad \ldots, \quad a_n = \frac{f^{(n)}(0)}{n!}.$$

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

$$\frac{1}{1-x} = 1 + x + x^2 + \cdots + x^n + \ldots.$$

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

$$f' = \frac{2}{x^3} e^{-1/x^2}, \quad f'' = e^{-1/x^2}\left[-\frac{6}{x^4} + \frac{4}{x^6}\right], \quad f''' = e^{-1/x^2} P_7(1/x), \quad \ldots.$$

So f is C^∞ away from $x = 0$. In particular, $f^{(n)}(x) \to 0$ as $x \to 0$ for all $n \geq 0$ since

$$\lim_{x \to 0} \frac{1}{x^m} e^{-1/x^2} = 0$$

for all $m \geq 0$. Now also

$$f'(0) = \lim_{x \to 0} \frac{e^{-1/x^2}}{x} = 0,$$

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 $n = 1, 2, \ldots,$ 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

$$|R_n(x)| = \frac{1}{(n+1)!}|f^{(n+1)}(\xi)||x - x_0|^{n+1} \leq \frac{1}{(n+1)}M^{n+1}R^{n+1} = \frac{(MR)^{n+1}}{(n+1)!} \to 0$$

as $n \to \infty$ since M, R are fixed. Thus we get the desired equality, since the error term goes to zero. □

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 $\rho : X \times X \to \mathbb{R}^+$ 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 $x_n \to x_0$ in (X, ρ) if $\rho(x_n, x_0) \to 0$ as $n \to \infty$. We write

$$\lim_{n \to \infty} x_n = x_0.$$

Example 14.2.1. If $x_n(t) \in C([a, b])$, then $x_n \to x_0$ means $x_n(t) \to x_0(t)$ uniformly in $[a, b]$.[1]

Definition 14.3. We say that $\{x_n\}$ is a *Cauchy sequence* in (X, ρ) if $\varphi(x_n, x_m) \to 0$ when $n, m \to \infty$, 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 $x_n \to x^*$, 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 $T : X \to Y$ is *continuous* if for any $\{x_n\}$ and $x_0 \in X$, we have $\rho(x_0, x_n) \to 0$ implies $r(T(x_0), T(x_n)) \to 0$.

[1] This is if we use the maximum norm from earlier.

Theorem 14.2. *A function $T : (X, \rho) \to (Y, r)$ 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

$$\begin{cases} \frac{dx}{dt} = F(t, x), \\ x(0) = \xi. \end{cases} \tag{1}$$

We would like to show that this ODE has a local solution.[2] To do this, we can transform the ODE into[3]

$$x(t) = \xi + \int_0^t f(\tau, x(\tau))\, d\tau.$$

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 $T : X \to X$ 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 $T : (X, \rho) \to (X, \rho)$ 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 $T : X \to X$ 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 principle[4])**.** *Let (X, ρ) be a complete metric space and $T : X \to X$ be a contraction mapping. Then T has a unique fixed point on X.*

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[2] The solution may not exist for longer time periods, e.g. it might blow up at some point.
[3] This process is called *Picard iteration*.
[4] This 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 $x_n \to x^* \in X$. Now we show that x^* is a fixed point of T. This is because $x_{n+1} = Tx_n$, and letting $n \to \infty$ 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. $x^* = x^{**}$. □

[5] One can show that any contraction mapping is continuous.

Lecture 15

Feb. 29 — Contraction Mapping

15.1 Newton's Method

Suppose we want to find a solution of $f(x) = 0$, for some differentiable function f. We can use *Newton's method*, which starts with some initial guess x_0, and iteratively computes better guesses. More precisely, we look at x_i, find the tangent line to f at x_i, and then take x_{i+1} to be the x-intercept of this line. The tangent line is given by

$$y = f(x_n) + f'(x_n)(x - x_n).$$

Setting $y = 0$ gives the recurrence

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}.$$

There are some nuances as to when Newton's method converges, since the x_i may end up oscillating or have some other problem if x_0 is badly chosen (e.g. if it is far away from the actual zero $\hat{x}$).

Example 15.0.1. Let $f \in C^2([a, b])$ and $\hat{x} \in (a, b)$ such that $f(\hat{x}) = 0$ and $f'(\hat{x}) \neq 0$. Then there exists a neighborhood of $\hat{x}$, denoted by $U(\hat{x})$, such that for all $x_0 \in U(\hat{x})$, the sequence

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

converges to $\hat{x}$ as $n \to \infty$.

Proof. Define the mapping

$$Tx = x - \frac{f(x)}{f'(x)}$$

in an interval containing $\hat{x}$, e.g. $I_\delta = [\hat{x} - \delta, \hat{x} + \delta]$. First we check that if δ is small, then $f : I_\delta \to I_\delta$. For this, let $x_1 = Tx$. If $|x - \hat{x}| < \delta$, then we have

$$|x_1 - \hat{x}| = |Tx - T\hat{x}| \leq a|x - \hat{x}| < \delta,$$

for some $0 < a < 1$. This is because for all $x_1, x_2 \in I_\delta$, letting $g(x) = Tx$, we have

$$|Tx_1 - Tx_2| = |g(x_1) - g(x_2)| = |g'(\xi)||x_1 - x_2|$$

for some $\xi \in I_\delta$ by the mean value theorem. Now notice that

$$|g'(\xi)| = \left|1 - \frac{f'(x)}{f'(x)} + \frac{f(x)f''(x)}{f'(x)^2}\right| = \left|\frac{f(x)f''(x)}{f'(x)^2}\right| < a < 1$$

if δ is small enough, since $f(x)$ is small in I_δ, and $f''(x)$ is bounded and $f'(x)$ is bounded away from zero. Then by the contraction mapping principle, we get the unique fixed point $\hat{x}$. $\square$

Remark. The rough idea is that $f'(x)$ is bounded away from zero in some open neighborhood U of $\hat{x}$ since $f'(\hat{x}) \neq 0$, and f' is continuous since $f \in C^2$. Now pick some compact interval $I \subseteq U$, and we get that f' must be bounded on I. This gives that f is Lipschitz, i.e. $|f(x) - f(y)| \leq L|x - y|$ for all $x, y \in I$ and some constant $L \in \mathbb{R}$. Then we just need to show that $0 < L < 1$.

15.2 Existence and Uniqueness for ODEs

Recall the ODE

$$\begin{cases} \frac{dx}{dt} = F(t, x). \\ x(0) = \xi. \end{cases}$$

We rewrite this into the integral form

$$x(t) = \xi + \int_0^t F(\tau, x(\tau))\, d\tau. \tag{$*$}$$

Now let $h > 0$ be some fixed constant that we choose later. Define $X = C([-h, h])$ and $T : X \to X$ by

$$(Tx)(t) = \xi + \int_0^t F(\tau, x(\tau))\, d\tau.$$

Then $(*)$ is equivalent to finding a fixed point of T. Assume $F(t, x)$ satisfies a *local Lipschitz condition*, i.e. there exist $\delta > 0$ and $L > 0$ such that when $|t| \leq h$, $|x_1 - \xi| \leq \delta$, and $|x_2 - \xi| \leq \delta$, we have

$$|F(t, x_1) - F(t, x_2)| \leq L|x_1 - x_2|.$$

Define

$$B(\xi, \delta) := \{x(t) \in C([-h, h]) \mid \max_{|t| \leq h} |x(t) - \xi| \leq \delta\}.$$

Think of this as the ball of radius δ around the constant function ξ in $C([-h, h])$. We want to check

(i) if h, δ are small enough, then $T : B(\xi, \delta) \to B(\xi, \delta)$,

(ii) and T is a contraction.

Once we do, then T has a unique fixed point $\hat{x}(t)$ by the contraction mapping principle, which is the solution of the ODE for $t \in [-h, h]$. For the first property, let

$$M = \max\{|F(t, x)| \mid t \in [-h, h] \times [\xi - \delta, \xi + \delta]\},$$

which exists since F is continuous and $[-h, h] \times [\xi - \delta, \xi + \delta]$ is compact. If h is small, then

$$\max_{t \in [-h, h]} |(Tx)(t) - \xi| = \max_{t \in [-h, h]} \left| \int_0^t F(\tau, x(\tau))\, d\tau \right| \leq Mh \leq \delta$$

since $t \leq h$. So $T : B(\xi, \delta) \to B(\xi, \delta)$. Now we show that T is a contraction. For any $x(t), y(t) \in B(\xi, \delta)$,

$$\begin{aligned} \rho(Tx, Ty) = \max_{t \in [-h, h]} \left| \int_0^t F(\tau, x(\tau)) - F(\tau, y(\tau))\, d\tau \right| &\leq h \max_{|t| \leq h} |F(t, x(t)) - F(t, y(t))| \\ &= Lh \max_{|t| \leq h} |x(t) - y(t)| = Lh\rho(x, y) \end{aligned}$$

by the Lipschitz condition. Now we can choose h such that $Lh < 1$, which ensures that T is a contraction.

Remark. This is called the *Picard-Lindelöf theorem*, or the *existence and uniqueness theorem for ODEs*.

15.3 Implicit Function Theorem

Example 15.0.2 (Implicit function theorem)**.** Let $f : \mathbb{R} \times \mathbb{R} \to \mathbb{R}$ and $U \times V \subseteq \mathbb{R} \times \mathbb{R}$ a neighborhood of (x_0, y_0). Assume f and $\partial f / \partial y$ are continuous on $U \times V$, and $f(x_0, y_0) = 0$ and

$$\frac{\partial f}{\partial y}(x_0, y_0) \neq 0.$$

Then there exists a neighborhood $U_0 \times V_0 \subseteq U \times V$ and a unique continuous function $\varphi : U_0 \to V_0$ satisfying

$$f(x, \varphi(x)) = 0, \quad \varphi(x_0) = y_0.$$

Proof. We want to solve $f(x, y) = 0$ in a neighborhood of (x_0, y_0). Define the mapping $\varphi \mapsto T\varphi$, where $\varphi \in C([x_0 - r, x_0 + r])$ for some $r > 0$. We take the definition

$$(T\varphi)(x) = \varphi(x) - \left(\frac{\partial f}{\partial y}(x_0, y_0)\right)^{-1} f(x, \varphi(x)).$$

Observe that if φ is a fixed point of T, then $f(x, \varphi(x)) = 0$. Let $X = C([x_0 - r, x_0 + r])$, and we will choose r later. For any $\varphi, \psi \in X$, define the distance

$$\rho(\varphi, \psi) = \max_{x \in [x_0 - r, x_0 + r]} |\varphi(x) - \psi(x)|.$$

Now we see that

$$\begin{aligned} \rho(T\varphi, T\psi) &= \max_{x \in [x_0 - r, x_0 + r]} \left| \varphi(x) - \psi(x) - \left(\frac{\partial f}{\partial y}(x_0, y_0)\right)^{-1} (f(x, \varphi(x)) - f(x, \psi(x))) \right| \\ &= \max_{x \in [x_0 - r, x_0 + r]} \left| \left(1 - \frac{\partial f}{\partial y}(x_0, y_0)^{-1} \frac{\partial f}{\partial y}(x, \hat{y})\right) (\varphi(x) - \psi(x)) \right| \end{aligned}$$

for some $\hat{y}$ between $\varphi(x)$ and $\psi(x)$ by the mean value theorem. Now define the ball

$$B(y_0, \delta) = \{\varphi \in C(x_0 - r, x_0 + r) \mid \rho(\varphi, y_0) \leq \delta\}.$$

If $\varphi, \psi \in B(y_0, \delta)$ and r, δ are small enough, then

$$\left| 1 - \frac{\partial f}{\partial y}(x_0, y_0)^{-1} \frac{\partial f}{\partial y}(x, \hat{y}) \right| < \frac{1}{2},$$

which ensures a contraction. So it only remains to check that $T : B(y_0, \delta) \to B(y_0, \delta)$. For $\varphi \in B(y_0, \delta)$,

$$\begin{aligned} \rho(T\varphi, y_0) &\leq \rho(T\varphi, Ty_0) + \varphi(Ty_0, y_0) \\ &\leq \frac{1}{2}\rho(\varphi, y_0) + \max_{x \in [x_0 - r, x_0 + r]} \left| \frac{\partial f}{\partial y}(x_0, y_0)^{-1} f(x, y_0) \right| \leq \frac{1}{2}\delta + \frac{1}{2}\delta = \delta \end{aligned}$$

if r is small enough since $f(x_0, y_0) = 0$. So $T\varphi \in B(y_0, \delta)$. Thus T is a contraction mapping on $B(y_0, \delta)$, so it has a unique fixed point by the contraction mapping principle. $\square$

Remark. The idea is that if $(\partial f / \partial y)(x_0, y_0) \neq 0$, then the solution set to $f(x, y) = 0$ in a neighborhood of (x_0, y_0) is given by the curve φ.

Lecture 16

Mar. 5 — The Derivative in $\mathbb{R}^n$

16.1 Partial Derivatives

Definition 16.1. Let f be a real-valued function defined on an open set $U \subseteq \mathbb{R}^n$. For a fixed point $a = (a_1, \ldots, a_n) \in U$, the *partial derivative* of f at a with respect to x_i is

$$\frac{\partial f}{\partial x_i}(a) = \lim_{x_i \to a_i} \frac{f(a_1, \ldots, a_{i-1}, x_i, a_{i+1}, \ldots, a_n) - f(a_1, \ldots, a_n)}{x_i - a_i} = \lim_{h \to 0} \frac{f(a + h\vec{e}_i) - f(a)}{h},$$

when this limit exists. Here $\vec{e}_i$ is the ith standard basis vector in $\mathbb{R}^n$.

Remark. The following are equivalent notations for partial derivatives:

$$\frac{\partial f}{\partial x_i}(a), \quad f_i'(a), \quad f_{x_i}, \quad D_i f.$$

Definition 16.2. The *gradient* of f at a is a vector of the partial derivatives, i.e.

$$\nabla f(a) = \left(\frac{\partial f}{\partial x_1}(a), \ldots, \frac{\partial f}{\partial x_n}(a) \right).$$

Remark. In one dimension, if $f(x)$ is differentiable at x_0, then $f(x)$ is continuous at x_0, because

$$\lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0} = f'(x_0),$$

which implies

$$f(x) - f(x_0) = f'(x_0)(x - x_0) + o(x - x_0).$$

As $x \to x_0$, the RHS goes to zero, so $f(x) \to f(x_0)$. However, this need not hold in higher dimensions. For $n \geq 2$, even if $\partial f / \partial x_i(a)$ exists for all $i = 1, 2, \ldots, n$, $f(x_0)$ might not be continuous at $x = a$.

Example 16.2.1. Consider the function

$$f(x, y) = \begin{cases} xy/(x^2 + y^2) & \text{if } (x, y) \neq (0, 0), \\ 0 & \text{if } (x, y) = (0, 0). \end{cases}$$

At $(0, 0)$, we have

$$\frac{\partial f}{\partial x}(0, 0) = \lim_{x \to 0} \frac{f(x, 0) - 0}{x} = \lim_{x \to 0} \frac{0 - 0}{x} = 0.$$

Similarly, $\partial f/\partial y(0,0) = 0$. But $f(x,y)$ is not continuous at $(0,0)$. For continuity, we need

$$\lim_{(x,y)\to(0,0)} f(x,y) = 0$$

when $(x,y) \to (0,0)$ along any path Γ from (x,y) to $(0,0)$. So it suffices to find two paths Γ_1 and Γ_2 with different limits to show that the limit does not exist. So choose $\Gamma : y = mx$. Then

$$\lim_{\substack{(x,y)\to(0,0)\\ \text{along } \Gamma}} \frac{x(mx)}{x^2 + m^2x^2} = \frac{m}{1+m^2}.$$

This limit clearly depends on m, so we can simply choose two different values of m to get differing limits. Hence we see that $f(x,y)$ is not continuous at $(0,0)$.

16.2 Differentiability

Definition 16.3. Let $f : U \to \mathbb{R}$ where $U \subseteq \mathbb{R}^n$ and $a = (a_1, \ldots, a_n) \in U$. Then f is *differentiable* at a if there exist constants $c_1, \ldots, c_n \in \mathbb{R}$ such that

$$\lim_{h\to 0} \frac{f(x) - (f(a) + c_1(x_1 - a_1) + \cdots + c_n(x_n - a_n))}{d(x,a)} = 0.$$

Here the distance is

$$d(x,a) = \sqrt{(x_1 - a_1)^2 + \cdots + (x_n - a_n)^2}.$$

Remark. If we let $\vec{c} = (c_1, \ldots, c_n)$, then the definition of differentiability becomes

$$f(x) = f(a) + \vec{c} \cdot (x - a) + o(d(x,a)).$$

We will soon show that in fact $\vec{c} = \nabla f(a)$.

Remark. In the one-dimensional case, for $f(x)$ where $x \in I \subseteq \mathbb{R}$, we defined the derivative as

$$\lim_{x\to a} \frac{f(x) - f(a)}{x - a} = f'(a).$$

This is equivalent to

$$\lim_{x\to a} \frac{f(x) - f(a) - f'(a)(x-a)}{|x-a|} = 0,$$

which is the same as our new definition for differentiability.

Proposition 16.1. *If $f(x)$ is differentiable at a, then $\partial f/\partial x_i(a)$ exists and $c_i = \partial f/\partial x_i(a)$.*

Proof. We can compute that

$$\frac{\partial f}{\partial x_i}(a) = \lim_{h\to 0} \frac{f(a + h\vec{e}_i) - f(a)}{h} = \lim_{h\to 0} \frac{f(a) + \vec{c}\cdot h\vec{e}_i + o(|h|) - f(a)}{h} = \lim_{h\to 0} \frac{\vec{c}\cdot h\vec{e}_i + o(|h|)}{h} = c_i,$$

which is the desired result. □

Proposition 16.2. *If $f(x)$ is differentiable at a, then $f(x)$ is continuous at a.*

Proof. From the definition, we have

$$f(x) = f(a) + \vec{c} \cdot (x - a) + o(d(x, a)).$$

As we take $x \to a$, we get $f(x) \to f(a)$ just as before. $\square$

Remark. If $f(x)$ is differentiable, then $f(x)$ has all partial derivatives $\partial f / \partial x_i$ at $x = a$. But the converse is not true in general. So differentiability is a strictly stronger condition in $\mathbb{R}^n$.

Lemma 16.1. *Let* $f : U \subseteq \mathbb{R}^n \to \mathbb{R}$*, where* U *is an open set. Then* f *is differentiable at* $x = a$ *if and only if there exist functions* $A_1, \ldots, A_n$ *on* U*, continuous at* $x = a$*, such that*

$$f(x) - f(a) = A_1(x)(x_1 - a_1) + A_2(x)(x_2 - a_2) + \cdots + A_n(x)(x_n - a_n)$$

for all $x \in U$*. In this case,* $\partial f / \partial x_i(a) = A_i(a)$*.*

Proof. ($\Rightarrow$) Assume $f(x)$ is differentiable at $x = a$. Then

$$\lim_{x \to a} \frac{f(x) - (f(a) + f_1'(a)(x_1 - a_1) + \cdots + f_n'(a)(x_n - a_n))}{d(x, a)} = 0.$$

Define the function $e : U \to \mathbb{R}$ via

$$e(x) = \frac{f(x) - (f(a) + f_1'(a)(x_1 - a_1) + \cdots + f_n'(a)(x_n - a_n))}{|x_1 - a_1| + \cdots + |x_n - a_n|}.$$

Observe that the denominator is a distance equivalent to $d(x, a)$.[1] Then $\lim_{x \to a} e(x) = 0$, since the distances are equivalent. Then we get

$$\begin{aligned} f(x) &= f(a) + f_1'(a)(x_1 - a_1) + \cdots + f_n'(a)(x_n - a_n) + e(x)(|x_1 - a_1| + \cdots + |x_n - a_n|) \\ &= f(a) + A_1(x)(x_1 - a_1) + \cdots + A_n(x)(x_n - a_n), \end{aligned}$$

where we define

$$A_i(x) = \begin{cases} f_i'(a) + e(x) & \text{if } x_i - a_i \geq 0 \\ f_i'(a) - e(x) & \text{if } x_i - a_i < 0. \end{cases}$$

Each A_i is continuous and satisfies $A_i(a) = f_i'(a)$, as desired.

($\Leftarrow$) Suppose $A_1, \ldots, A_n$ exist such that

$$f(x) - f(a) = A_1(x)(x_1 - a_1) + \cdots + A_n(x)(x_n - a_n).$$

We check that f is differentiable at $x = a$. Choose $c_i = A_i(a)$. Then

$$\left| \frac{f(x) - (f(a) - \sum_{i=1}^n c_i(x_i - a_i))}{d(x, a)} \right| = \left| \frac{\sum_{i=1}^n (A_i(x) - A_i(a))(x_i - a_i)}{d(x, a)} \right| \leq \sum_{i=1}^n |A_i(x) - A_i(a)| \to 0$$

as $x \to a$, since each A_i is continuous at a. Thus f is differentiable at $x = a$. $\square$

[1] Two metrics (distances) $d_1, d_2 : X \times X \to \mathbb{R}$ on a set X are *equivalent* if there exist constants $c, C \in \mathbb{R}$ such that $c d_1(x, y) \leq d_2(x, y) \leq C d_1(x, y)$ for all $x, y \in X$.

Theorem 16.1. *Let U be an open set in $\mathbb{R}^n$ and suppose that $f : U \to \mathbb{R}$ has partial derivatives $f_1', \ldots, f_n'$ on U which are continuous at $x = a$. Then f is differentiable at $x = a$.*

Proof. We change x_i to a_i one by one to get

$$\begin{aligned} f(x) - f(a) = (&f(x_1, \ldots, x_n) - f(a_1, x_2, \ldots, x_n)) \\ &+ (f(a_1, x_2, \ldots, x_n) - f(a_1, a_2, x_3, \ldots, x_n)) \\ &+ (f(a_1, a_2, x_3, \ldots, x_n) - f(a_1, a_2, a_3, x_4, \ldots, x_n)) \\ &\quad \vdots \\ &+ (f(a_1, \ldots, a_{n-1}, x_n) - f(a_1, \ldots, a_n)). \end{aligned}$$

Each of these terms differ in only one variable, so we can apply the mean value theorem to get

$$\begin{aligned} f(x) - f(a) = &f_1'(\xi_1, a_2, \ldots, a_n)(x_1 - a_1) \\ &+ f_2'(a_1, \xi_2, a_3, \ldots, a_n)(x_2 - a_2) \\ &\quad \vdots \\ &+ f_n'(a_1, \ldots, a_{n-1}, \xi_n)(x_n - a_n). \end{aligned}$$

So we can set

$$\begin{aligned} A_1(x) &= f_1'(\xi_1, a_2, \ldots, a_n)(x_n - a_n) \\ A_2(x) &= f_2'(a_1, \xi_2, a_3, \ldots, a_n)(x_n - a_n) \\ &\vdots \\ A_n(x) &= f_n'(a_1, \ldots, a_{n-1}, \xi_n)(x_n - a_n). \end{aligned}$$

where ξ_i is between a_i and x_i for each $1 \le i \le n$. Each A_i is continuous since each f_i' is continuous, so we get $A_i(x) \to A_i(a)$ when $x \to a$. So $f(x)$ is differentiable at $x = a$. $\square$

Remark. In functional analysis, there is an analogous theorem that relates the Gâteaux derivative (similar to a partial derivative) and the Fréchet derivative (similar to differentiability).

Remark. The existence of continuous partial derivatives at $x = a$ is a sufficient condition for differentiability at $x = a$, but it is not necessary.

Example 16.3.1. Consider the function

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

First we verify that f is differentiable at $(x, y) = (0, 0)$. We can compute

$$|f(x, y) - f(0, 0)| = (x^2 + y^2)\left|\sin \frac{1}{x^2 + y^2}\right| = O((\sqrt{x^2 + y^2})^2),$$

so f is differentiable at $(0, 0)$, with the zero linear approximation $f(x, y) \approx 0x + 0y$. This also gives $f_1'(0, 0) = f_2'(0, 0) = 0$. However, if $(x, y) \neq (0, 0)$, then

$$f_x(x, y) = 2x \sin \frac{1}{x^2 + y^2} - \frac{2x}{x^2 + y^2} \cos \frac{1}{x^2 + y^2}$$

by the product rule. Letting $(x, y) \to 0$, we see that the second term on the RHS has no limit. For example, along $y = 0$, we get

$$\frac{2x}{x^2 + y^2} \cos \frac{1}{x^2 + y^2}\bigg|_{y=0} = \frac{2}{x} \cos \frac{1}{x^2},$$

which has no limit as $x \to 0$. So $f_x(x, y)$ is not continuous at $(0, 0)$. By symmetry, $f_y(x, y)$ is also not continuous at $(0, 0)$. So a function f can be differentiable at $x = a$ while its partial derivatives $f_i'(x)$ are not continuous at $x = a$.

Lecture 17

Mar. 7 — Vector-Valued Functions

17.1 The Derivative for Vector-Valued Functions

Definition 17.1. Let $f : U \subseteq \mathbb{R}^n \to \mathbb{R}^m$, where U is an open set. We say $f = (f_1, \dots, f_m)$ is *differentiable* if each f_i is differentiable. In other words, for $x, a \in U$,

$$f(x) - f(a) = \begin{pmatrix} \partial f_1/\partial x_1(a) & \dots & \partial f_1/\partial x_n(a) \\ \vdots & \ddots & \vdots \\ \partial f_m/\partial x_1(a) & \dots & \partial f_m/\partial x_n(a) \end{pmatrix} (x-a) + o(|x-a|).$$

We may call the matrix of partial derivatives $f'(a)$ or $\partial f/\partial x$.

Theorem 17.1 (Chain rule)**.** *Let U, V be open sets in $\mathbb{R}^n$ and $\mathbb{R}^m$, respectively, and $f : U \to V$, $g : V \to \mathbb{R}$ be functions. Let $a \in U$ such that f is differentiable at a and g is differentiable at $f(a)$. Then $g \circ f(x) = g(f(x))$ is differentiable at a, and*

$$(g \circ f)'_j(a) = \sum_{i=1}^{m} g'_i(f(a))(f_i)'_j(a),$$

where $(f_i)'_j$ denotes $\partial f_i/\partial x_j$.

Proof. See textbook (Rosenlicht). □

Remark. In matrix notation, we can write this via

$$\nabla(g \circ f) = \nabla g \frac{\partial f}{\partial x},$$

where ∇g is a vector in $\mathbb{R}^m$ and $\partial f/\partial x$ is an $m \times n$ matrix.

Remark. When $f : U \subseteq \mathbb{R}^n \to \mathbb{R}^n$, we get

$$\frac{\partial f}{\partial x}(a) = \begin{pmatrix} \partial f_1/\partial x_1(a) & \dots & \partial f_1/\partial x_n(a) \\ \vdots & \ddots & \vdots \\ \partial f_n/\partial x_1(a) & \dots & \partial f_n/\partial x_n(a) \end{pmatrix},$$

an $n \times n$ matrix. So we can take its determinant, and we call $\det(\partial f/\partial x)$ the *Jacobian* of f.

17.2 Implicit Function Theorem in $\mathbb{R}^n$

Remark. Recall Theorem 15.0.2, the implicit function theorem on $\mathbb{R}$. Note that all solutions to $f(x,y)=0$ are in fact given by the continuous curve $y=\varphi(x)$ in a neighborhood of (x_0,y_0). To see this, suppose $f(x,y)-f(x,\varphi(x))=0$ for some y. Fixing x, by the mean value theorem we get

$$\frac{\partial f}{\partial y}(x,\xi)(y-\varphi(x))=0.$$

Since $\partial f/\partial y(x,\xi)\neq 0$, this implies $y=\varphi(x)$. So there are no solutions off of the curve.

Theorem 17.2. *Let $f:\mathbb{R}^n\times\mathbb{R}^m\to\mathbb{R}^m$ and $U\times V\subseteq\mathbb{R}^n\times\mathbb{R}^m$ be a neighborhood of (x_0,y_0). Suppose f and $\partial f/\partial y$ are continuous on $U\times V$, and $f(x_0,y_0)=0$ and*

$$\det\left(\frac{\partial f}{\partial y}(x_0,y_0)\right)\neq 0.$$

Then there exists a neighborhood $U_0\times V_0\subseteq U\times V$ of (x_0,y_0) and a unique continuous function $\varphi:U_0\to V_0$ satisfying

$$\begin{cases} f(x,\varphi(x))=0,\\ \varphi(x_0)=y_0.\end{cases}$$

Proof. Take $T:\varphi\mapsto T\varphi$, where $\varphi\in C(\overline{B(x_0,r)},\mathbb{R}^m)$ and[1]

$$\rho(\varphi,\psi)=\max_{\substack{x\in B(x_0,r)\\ 1\leq i\leq m}}|\varphi_i(x)-\psi_i(x)|$$

is the metric. Define

$$(T\varphi)(x)=\varphi(x)-\left(\frac{\partial f}{\partial y}(x_0,y_0)\right)^{-1}f(x,\varphi(x)).$$

Note that this is a matrix inverse. Define

$$X=\{\varphi\in C(\overline{B(x_0,r)},\mathbb{R}^m):\rho(\varphi,y_0)\leq\delta\}$$

Now it suffices to show that

1. $\rho(T\varphi,T\psi)\leq\frac{1}{2}\rho(\varphi,\psi)$ for r,δ small enough,
2. and $T:X\to X$

in order to apply the contraction mapping theorem and finish.[2] Check these two details as an exercise. $\square$

Corollary 17.2.1 (Inverse function theorem)**.** *If $f:U\subseteq\mathbb{R}^n\to\mathbb{R}^n$ such that $f,\partial f/\partial y$ are continuous in a neighborhood of $y_0\in U$ and $\det(\partial f/\partial y(y_0))\neq 0$, then there exists $g:V\to\mathbb{R}^n$, where V is a neighborhood of $f(y_0)$, such that $g\circ f=\mathrm{id}$, i.e. $g(f(x))=x$.*

Proof. Let $F(x,y)=x-f(y)$, and we want to solve $F(x,y)=0$ near the point $(f(y_0),y_0)$. Apply the implicit function theorem to F to finish. See textbook (Rosenlicht) for details. $\square$

[1]Recall that $\overline{A}$ is the *closure* of a set A, i.e. the smallest closed set containing A.

[2]The continuity of φ is implied since it is a fixed point in a function space of continuous functions.

17.3 Higher Order Derivatives

Definition 17.2. If $f : U \subseteq \mathbb{R}^n \to \mathbb{R}$ and $\partial f/\partial x_i$ is differentiable with respect to x_j, then we can define[3]

$$\frac{\partial}{\partial x_j}\left(\frac{\partial f}{\partial x_i}\right) = \frac{\partial^2 f}{\partial x_j \partial x_i} = f_{x_j x_i}.$$

These are the *second order partial derivatives.* Similarly, we can define higher order partial derivatives.

Remark. We want to know: When is $f_{x_j x_i} = f_{x_i x_j}$ (i.e. $(f'_i)'_j = (f'_j)'_i$)?

Theorem 17.3. *Let $f : U \subseteq \mathbb{R}^n \to \mathbb{R}$ and $a \in U$. If $(f'_i)'_j$ and $(f'_j)'_i$ exist and are continuous in a neighborhood of a, then*

$$(f'_i)'_j(a) = (f'_j)'_i(a).$$

Proof. Take a point $x = (x_1, x_2) \neq a$ in a small neighborhood of $a = (a_1, a_2)$. Define

$$\Delta(x) = \frac{f(x_1, x_2) - f(x_1, a_2) - f(a_1, x_2) + f(a_1, a_2)}{(x_1 - a_1)(x_2 - a_2)}.$$

Let $\varphi(x_1, x_2) = f(x_1, x_2) - f(x_1, a_2)$, so that

$$\Delta x = \frac{\varphi(x_1, x_2) - \varphi(a_1, x_2)}{(x_1 - a_1)(x_2 - a_2)}.$$

by the mean value theorem,

$$\varphi(x_1, x_2) - \varphi(a_1, x_2) = (x - a_1)\varphi'_1(\xi_1, x_2)$$

for some ξ_1 between x_1 and a_1. Then

$$\Delta x = \frac{\varphi'_1(\xi_1, x_2)}{x_2 - a_2} = \frac{f'_1(\xi_1, x_2) - f'_1(\xi_1, a_2)}{x_2 - a_2} = (f'_1)'_2(\xi_1, \xi_2)$$

by the mean value theorem again, for some ξ_2 between a_2 and x_2. In the same manner, we get

$$\Delta x = (f'_2)'_1(\xi'_1, \xi'_2),$$

where (ξ'_1, ξ'_2) is in a neighborhood of a. Now let $(x_1, x_2) \to (a_1, a_2)$, then $(\xi_1, \xi_1), (\xi'_1, \xi'_2) \to (a_1, a_2)$. By assumption, $(f'_2)'_1(\xi'_1, \xi'_2) \to (f'_2)'_1(a)$ and $(f'_1)'_2(\xi_1, \xi_2) \to (f'_1)'_2(a)$ since $(f'_2)'_1$ and $(f'_1)'_2$ are continuous, so

$$(f'_1)'_2(a) = (f'_2)'_1(a)$$

since $(f'_2)'_1(\xi'_1, \xi'_2) = (f'_1)'_2(\xi_1, \xi_2) = \Delta x.$ ∎

[3] Note the indices, we have $f_{x_j x_i} = (f'_i)'_j$.

Lecture 18

Mar. 12 — More on the Implicit Function Theorem

18.1 Example of Unequal Mixed Partial Derivatives

Example 18.0.1. Consider the function.

$$f(x,y) = \begin{cases} xy(x^2-y^2)/(x^2+y^2) & \text{if } x^2+y^2 \neq 0 \\ 0 & \text{if } x^2+y^2 = 0. \end{cases}$$

We find

$$f'_x(x,y) = \begin{cases} y((x^2-y^2)(x^2+y^2)+4x^2y^2/(x^2+y^2)^2) & \text{if } x^2+y^2 \neq 0 \\ 0 & \text{if } x^2+y^2 = 0. \end{cases}$$

and

$$f'_y(x,y) = \begin{cases} x((x^2-y^2)(x^2+y^2)+4x^2y^2/(x^2+y^2)^2) & \text{if } x^2+y^2 \neq 0 \\ 0 & \text{if } x^2+y^2 = 0. \end{cases}.$$

Now $f'_x(0,y) = -y$ and so $f''_{xy}(0,0) = -1$, but $f'_y(x,0) = x$ and so $f''_{yx}(0,0) = 1$. Thus $f''_{xy}(0,0) \neq f''_{yx}(0,0)$.

18.2 Revisiting the Implicit Function Theorem

Theorem 18.1 (Mean value theorem in $\mathbb{R}^n$)**.** *Suppose $f : U \subseteq \mathbb{R}^n \to \mathbb{R}$ where U is open, and that f is differentiable. Then for any $a, b \in U$, there exists ξ on the line segment connecting a, b such that*

$$f(a) - f(b) = \nabla f(\xi) \cdot (a-b).$$

Proof. Define $h(t) = f(ta + (1-t)b)$ for $t \in [0,1]$. Then

$$f(a) - f(b) = h(1) - h(0) = h'(c) = \nabla f(ca + (1-c)b) \cdot (a-b)$$

for some $c \in (0,1)$ by the usual mean value theorem. So we can pick $\xi = ca + (1-c)b$. □

The following is a corollary of Theorem 17.2:

Corollary 18.1.1. *If $f_1, \ldots, f_n$ are continuously differentiable in a neighborhood of (a,b), then U, V can be chosen such that $\varphi : U \to V$ is continuously differentiable, i.e. $\varphi \in C^1(U,V)$.*[1]

[1] In the notation of Theorem 17.2, we had $f = (f_1, \ldots, f_n)$, (x_0, y_0) instead of (a,b), and U_0, V_0 instead of U, V.

Proof. Recall that

$$\begin{cases} f_i(x, \varphi(x)) = 0 \\ \varphi(a) = b \end{cases}$$

for all $1 \le i \le n$. Then we have

$$\begin{aligned} 0 = f_i(x, \varphi(x)) - f_i(a, \varphi(a)) = & \frac{\partial f_i}{\partial x_1}(z^i)(x_1 - a_1) + \cdots + \frac{\partial f_i}{\partial x_m}(z^i)(x_m - a_m) \\ & + \frac{\partial f_i}{\partial y_1}(z^i)(\varphi_1(x) - b_1) + \cdots + \frac{\partial f_i}{\partial y_n}(z^i)(\varphi_n(x) - b_n) \end{aligned}$$

where z_i is between $(x, \varphi(x))$ and (a, b). Now since $\det(\partial f/\partial y_j(z^i)) \neq 0$, we can solve this linear system to get

$$\varphi_i(x) - b_i = A_{i1}(x)(x_1 - a_1) + A_{i2}(x)(x_2 - a_2) + \cdots + A_{im}(x)(x_m - a_m),$$

where the coefficient functions $A_{i1}, \ldots, A_{im}$ are continuous in a neighborhood of a by assumption. So $\varphi(x) = (\varphi_1(x), \ldots, \varphi_n(x))$ is continuously differentiable in a neighborhood of a, as desired. $\square$

Remark. We can improve this if we know f is more smooth. In general, if $f \in C^k$, then $\varphi \in C^k$ also.

Example 18.0.2 (Implicit differentiation)**.** Suppose $F(x, y) = 0$ and $y = \varphi(x)$. If $F \in C^1$ and $F'_y \neq 0$,

$$\frac{d}{dx} F(x, \varphi(x)) = 0 \implies F'_x + F'_y \varphi_x = 0 \implies \varphi_x = -\frac{F'_x}{F'_y}.$$

We can justify this rigorously via the implicit function theorem.

18.3 Lagrange Multipliers

Recall from multivariable calculus that we can use the method of Lagrange multipliers to solve the minimum (or maximum) of a function $f(x, y)$ subject to a constraint $g(x, y) = 0$. The *Lagrange multiplier equation* is

$$\begin{cases} \nabla f = \lambda \nabla g \\ g = 0, \end{cases}$$

which is a system of three equations in (x, y, λ). Here λ is called the *Lagrange multiplier.*

Proposition 18.1. *Assume that at a local minimum (or maximum) point (x_0, y_0) of f, we have*

$$\nabla g(x_0, y_0) \neq \vec{0},$$

i.e. $g_x^2(x_0, y_0) + g_y^2(x_0, y_0) \neq 0$. Then there exists λ such that $\nabla f = \lambda \nabla g$ at (x_0, y_0).

Proof. Assume $g'_y(x_0, y_0) \neq 0$. Then by the implicit function theorem, there exists some $y = \varphi(x)$ in a neighborhood of y_0 such that $g(x, \varphi(x)) = 0$. Then $h(x) = f(x, \varphi(x))$ obtains a minimum (or maximum) at x_0. Then $h'(x_0) = 0$, so

$$f'_x(x_0, y_0) + f'_y(x_0, y_0)\varphi'_x(x_0) = 0.$$

Also, by implicit differentiation,

$$\varphi'_x(x_0) = -\frac{g'_x(x_0, y_0)}{g'_y(x_0, y_0)}.$$

So we can set

$$\lambda = -\frac{f'_y(x_0, y_0)}{g'_y(x_0, y_0)} \implies \begin{cases} f'_x(x_0, y_0) + \lambda g'_x(x_0, y_0) = 0 \\ f'_y(x_0, y_0) + \lambda g'_y(x_0, y_0) = 0. \end{cases}$$

Thus we have $(\nabla f + \lambda \nabla g)(x_0, y_0) = 0$, as desired. $\square$

Remark. The condition $\nabla g(x_0, y_0) \neq \vec{0}$ is necessary to derive the Lagrange multiplier equation.

Example 18.0.3. Minimize $f(x, y) = x^2 + y^2$ subject to $g = (x-1)^3 - y^2 = 0$. The distance of g to the origin is clearly minimized at $(1, 0)$, but we have

$$\nabla g(1, 0) = (3(x-1)^2, -2y)\big|_{(1,0)} = (0, 0)$$

and $\nabla f(1, 0) = (2, 0)$. So $\nabla f \neq \lambda \nabla g$ in this case since $\nabla g(1, 0) = \vec{0}$.

Remark. So in general, we should also check the points where $\nabla g = \vec{0}$ separately.

Theorem 18.2. *Suppose $f(x_1, \ldots, x_n)$ obtains a local minimum (or maximum) at $p^0 = (x_1^{(0)}, \ldots, x_n^{(0)})$ subject to*

$$\begin{cases} g_1(x_1, \ldots, x_n) = 0 \\ \quad \vdots \\ g_m(x_1, \ldots, x_n) = 0, \end{cases}$$

where $m < n$. Assume that $f, g_i \in C^1$ in a neighborhood of p^0 and the matrix

$$\frac{\partial g}{\partial x}(p^0) = \begin{pmatrix} \partial g_1/\partial x_1 & \ldots & \partial g_1/\partial x_n \\ \vdots & \ddots & \vdots \\ \partial g_m/\partial x_1 & \ldots & \partial g_m/\partial x_n \end{pmatrix}(p^0)$$

has rank m. Then there exist $\lambda_1, \ldots, \lambda_m$ such that

$$\begin{cases} (\nabla f + \lambda_1 \nabla g_1 + \cdots + \lambda_m \nabla g_m)(p^0) = 0 \\ g_i(p^0) = 0. \end{cases}$$

Proof. We prove this in the case of four unknowns and two constraints (the proof can be generalized). Consider

$$\text{minimize (or maximize) } f(x, y, z, t) \quad \text{subject to} \quad \begin{cases} \varphi(x, y, z, t) = 0 \\ \psi(x, y, z, t) = 0. \end{cases}$$

Suppose the minimum (or maximum) of f is obtained at $p^0 = (x_0, y_0, z_0, t_0)$. Then by assumption, there are two variables (say z, t) such that

$$\det \frac{\partial(\varphi, \psi)}{\partial(z, t)}\bigg|_{p^0} \neq 0.$$

Then by the implicit function theorem, we can find $z = g(x, y)$ and $t = h(x, y)$ such that the constraint equations are satisfied. Then $u(x, y) = f(x, y, z(x, y), t(x, y))$ obtains a minimum (or maximum) at (x_0, y_0), so

$$\nabla u(x_0, y_0) = 0 \implies \begin{cases} f'_x + f'_z(\partial z/\partial x) + f'_t(\partial t/\partial x) = 0 \\ f'_y + f'_z(\partial z/\partial y) + f'_t(\partial t/\partial y) = 0. \end{cases} \tag{1, 2}$$

Then

$$\begin{cases} \varphi'_x + \varphi'_z(\partial z/\partial x) + \varphi'_t(\partial t/\partial x) = 0 \\ \psi'_x + \psi'_z(\partial z/\partial x) + \psi'_t(\partial t/\partial x) = 0. \end{cases} \quad \text{and} \quad \begin{cases} \varphi'_y + \varphi'_z(\partial z/\partial y) + \varphi'_t(\partial t/\partial y) = 0 \\ \psi'_y + \psi'_z(\partial z/\partial y) + \psi'_t(\partial t/\partial y) = 0. \end{cases} \tag{$\star$}$$

Since $\det(\partial(\varphi,\psi)/\partial(z,t)) \neq 0$ at p^0, we can find λ, μ such that

$$\begin{cases} f'_z + \lambda\varphi'_z + \mu\psi'_z = 0 \\ f'_t + \lambda\varphi'_t + \mu\psi'_t = 0, \end{cases}$$

which is always possible since the coefficient matrix is nonsingular. Let (A) and (B) be the two systems in $(\star)$ and A_1, A_2 and B_1, B_2 be their first and second equations, respectively. Then look at the equation $\lambda(A_1) + \mu(A_2) + (1)$, which gives

$$f'_x + \lambda\varphi'_x + \mu\psi'_x + \underbrace{(f'_z + \lambda\varphi'_z + \mu\psi'_z)}_{=0}\frac{\partial z}{\partial x} + \underbrace{(f'_t + \lambda\varphi'_t + \mu\psi'_t)}_{=0}\frac{\partial t}{\partial x} = 0.$$

This implies that $f'_x + \lambda\varphi'_x + \mu\psi'_x = 0$, and we can similarly get that $f'_y + \lambda\varphi'_y + \mu\psi'_y = 0$. Thus we end up with $\nabla f + \lambda\nabla\varphi + \mu\nabla\psi = 0$ at p^0, as desired. $\square$

Lecture 19

Mar. 14 — The Riemann Integral in $\mathbb{R}^n$

19.1 Defining the Riemann Integral in $\mathbb{R}^n$

Definition 19.1. A *closed interval*, or a *rectangular domain*, in $\mathbb{R}^n$ is a set of the form

$$\{(x_1, \dots, x_n) : a_1 \le x_i \le b_i \text{ for } i = 1, 2, \dots, n\}.$$

A *partition* of I is a partition of each $[a_i, b_i]$ for $i = 1, 2, \dots, n$, i.e.

$$(x_1^0, x_1^1, \dots, x_1^{N_1}, \quad (x_2^0, x_2^1, \dots, x_2^{N_2}), \quad \dots, \quad (x_n^0, x_n^1, \dots, x_n^{N_n}).$$

The *width* of a partition I is $\max\{x_i^j - x_i^{j-1} : i = 1, \dots, n,\ j = 1, \dots, n\}$. A *Riemann sum* is then

$$S = \sum_{\substack{j_1 = 1, \dots, N_1 \\ j_2 = 1, \dots, N_2 \\ \dots \\ j_n = 1, \dots, N_n}} f(y_1^{j_1, \dots, j_n}, y_2^{j_1, \dots, j_n}, \dots, y_n^{j_1, \dots, j_n})(x_1^{j_1} - x_1^{j_1 - 1}) \dots (x_n^{j_n} - x_n^{j_n - 1})..$$

Definition 19.2. We say $f : I \subseteq \mathbb{R}^n \to \mathbb{R}$ is *Riemann integrable*, where I is a rectangular domain, if there exists $A \in \mathbb{R}$ such that for any $\epsilon > 0$, there exists $\delta > 0$ such that $|S - A| < \epsilon$ for any Riemann sum S with partition width $< \delta$. In this case, we write

$$A = \int_I f(x)\, dx_1 \dots dx_n = \int_I f\, dx.$$

Remark. The Riemann integral in $\mathbb{R}^n$ is still uniquely defined, when it exists. If A, A' both satisfy the definition, then for every $\epsilon > 0$, there exists a Riemann sum S such that $|S - A| < \epsilon$ and $|S - A'| < \epsilon$. Then $|A - A'| < 2\epsilon$ by the triangle inequality, which implies that $A = A'$ since ϵ was arbitrary.

Example 19.2.1. If $f(x) \equiv c$, then we have

$$\int_I f\, dx = c(b_1 - a_1) \dots (b_n - a_n).$$

Example 19.2.2. Consider $f(x) = 0$ if $x_1 \ne \xi_1$ for some $\xi_1 \in \mathbb{R}$, i.e. zero except on a single hyperplane. Then we have

$$\int_I f\, dx = 0.$$

This remains true if $x_i \ne \xi_i$ for any single fixed $1 \le i \le n$.

Example 19.2.3 (Simple step functions)**.** Let $\alpha_1, \dots, \alpha_n, \beta_1, \dots, \beta_n \in \mathbb{R}$ such that $a_i \le \alpha_i \le \beta_i \le b_i$ for each $i = 1, 2, \dots, n$. Then we can define $f : I \to \mathbb{R}$ by

$$f(x_1, \dots, x_n) = \begin{cases} 1 & \text{if } x_i \in (\alpha_i, \beta_i) \text{ for } i = 1, 2, \dots, n, \\ 0 & \text{otherwise.} \end{cases}.$$

We call such a function a *simple step function*. In this case, we have

$$\int_I f\,dx = (\beta_1 - \alpha_1) \dots (\beta_n - \alpha_n).$$

Example 19.2.4. Of course not all functions are Riemann integrable in $\mathbb{R}^n$ either. Let I be a closed interval in $\mathbb{R}^n$ and define $f : I \to \mathbb{R}$ by

$$f(x) = \begin{cases} 1 & \text{if } x = (x_1, \dots, x_n) \in I \text{ and } x_1, \dots, x_n \text{ are rational,} \\ 0 & \text{otherwise.} \end{cases}$$

This function f is not Riemann integrable.

19.2 Properties of the Riemann Integral in $\mathbb{R}^n$

Proposition 19.1. *We have the following:*

1. *If $f, g \in \mathcal{R}(I)$, $I \subseteq \mathbb{R}^n$, then $f + g \in \mathcal{R}(I)$ and*

$$\int_I (f+g)\,dx = \int_I f\,dx + \int_I g\,dx.$$

2. *If $f \in \mathcal{R}(I)$ and $c \in \mathbb{R}$, then $cf \in \mathcal{R}(I)$ and*

$$\int_I cf\,dx = c\int_I f\,dx.$$

3. *If $f \ge 0$ on I and $f \in \mathcal{R}(I)$, then*

$$\int_I f\,dx \ge 0.$$

4. *If $f \le g$ on I and $f, g \in \mathcal{R}(I)$, then*

$$\int_I f\,dx \le \int_I g\,dx.$$

5. *If $m \le f \le M$ and $f \in \mathcal{R}(I)$, then*

$$m\,\mathrm{Vol}(I) \le \int_I f\,dx \le M\,\mathrm{Vol}(I),$$

where $\mathrm{Vol}(I) = (b_1 - a_1) \dots (b_n - a_n)$.

Proof. Check these properties as an exercise. $\square$

19.3 Conditions for Riemann Integrability in $\mathbb{R}^n$

Lemma 19.1. *Let I be a closed interval in $\mathbb{R}^n$. Then $f \in \mathcal{R}(I)$ if and only if for all $\epsilon > 0$, there exists $\delta > 0$ such that $|S_1 - S_2| < \epsilon$ whenever S_1, S_2 are two Riemann sums with partitions of width $< \delta$.*

Proof. Roughly the same idea as in $\mathbb{R}$, see Rosenlicht for details. □

Example 19.2.5 (General step functions)**.** Let $(x_1^0, x_1^1, \ldots, x_1^{N_1}), \ldots, (x_n^0, x_n^1, \ldots, x_n^{N_n})$ be a partition of I. A *step function* $f : I \to \mathbb{R}$ is defined by

$$f(x) = \begin{cases} c_{j_1,\ldots,j_n} & \text{if } x_i^{j_1-1} < x_i < x_i^{j_i} \text{ for all } i = 1, 2, \ldots, n \\ 0 & \text{otherwise} \end{cases}$$

for some constants $c_{j_1,\ldots,j_n} \in \mathbb{R}$. Observe that f is a linear combination of simple step functions, so it is integrable. To be more precise, notice that we can write

$$f = \sum c_{j_1,\ldots,j_n} f_{j_1,\ldots,j_n}, \quad \text{where} \quad f_{j_1,\ldots,j_n}(x) = \begin{cases} 1 & \text{if } x_i^{j_i-1} < x_i < x_i^{j_i} \text{ for all } i = 1, 2, \ldots, n, \\ 0 & \text{otherwise.} \end{cases}$$

Then we get

$$\int_I f\,dx = \sum_{\substack{1 \le j_i \le N_i \\ 1 \le i \le n}} c_{j_1,\ldots,j_n} (x_1^{j_1} - x_1^{j_1-1}) \ldots (x_n^{j_n} - x_n^{j_n-1}).$$

Proposition 19.2. *Let $I \subseteq \mathbb{R}^n$ be a closed interval and $f : I \to \mathbb{R}$. Then $f \in \mathcal{R}(I)$ if and only if for any $\epsilon > 0$, there exist step functions f_1, f_2 on I such that $f_1(x) \le f(x) \le f_2(x)$ for all $x \in I$ and*

$$\int_I (f_2 - f_1)\,dx < \epsilon.$$

Proof. Similar to the proof in $\mathbb{R}$, see Rosenlicht for details. □

Corollary 19.0.1. *If I is a closed interval $f \in \mathcal{R}(I)$, then f is bounded on I.*

Proof. This follows from the proof of Proposition 19.2, like in the case of $\mathbb{R}$. □

Corollary 19.0.2. *Let $I \subseteq J$ be closed intervals in $\mathbb{R}^n$ and $f : J \to \mathbb{R}$ such that $f(x) = 0$ if $x \in J \setminus I$. Then $f \in \mathcal{R}(J)$ if and only if $f \in \mathcal{R}(I)$. Moreover, in this case we have*

$$\int_I f\,dx = \int_J f\,dx.$$

Proof. ($\Leftarrow$) Suppose $f \in \mathcal{R}(I)$. Then for any $\epsilon > 0$, there exist two step functions f_1, f_2 on I such that $f_1(x) \le f(x) \le f_2(x)$ for all $x \in I$ and

$$\int_I (f_2 - f_1)\,dx < \epsilon.$$

Extend the step functions f_1, f_2 to J by setting $f_1(x) = f_2(x) = 0$ if $x \in J \setminus I$. Note that f_1, f_2 become step functions on J if we extend them in this manner. Since $f \equiv 0$ on $J \setminus I$, we have $f_1(x) \le f(x) \le f_2(x)$ for all $x \in J$, and

$$\int_J (f_2 - f_1)\, dx = \int_I (f_2 - f_1)\, dx < \epsilon.$$

So $f \in \mathcal{R}(J)$. To see that the two integrals are the same, observe that

$$\int_I f_1 \le \int_I f \le \int_I f_2 \quad \text{and} \quad \int_I f_1 = \int_J f_1 \le \int_J f \le \int_J f_2 = \int_I f_2,$$

so we get

$$\left| \int_I f - \int_J f \right| \le \int_I (f_2 - f_1) < \epsilon \implies \int_I f = \int_J f$$

since ϵ was arbitrary.

($\Rightarrow$) Suppose $f \in \mathcal{R}(J)$. Then for any $\epsilon > 0$, there exist step functions f_1, f_2 on J such that

$$f_1(x) \le f(x) \le f_2(x) \text{ for all } x \in J \quad \text{and} \quad \int_J (f_2 - f_1) < \epsilon.$$

Define g_1, g_2 on I by restricting f_1, f_2 to I. Then g_1, g_2 are step functions on I and $g_1 \le f \le g_2$ on I. Now we also have

$$\int_I (g_2 - g_1) = \int_I (f_2 - f_1) \le \int_J (f_2 - f_1) < \epsilon$$

since $f_1 \le f_2$, so $f_2 - f_1 \ge 0$ on J. This gives $f \in \mathcal{R}(I)$. $\square$

19.4 Extending the Integral

Definition 19.3. If $f : \mathbb{R}^n \to \mathbb{R}$ and $f \equiv 0$ outside a bounded set (bounded support),[1] then there exists a closed interval $I \subseteq \mathbb{R}^n$ such that $f(x) = 0$ outside I. Then we say f is *integrable on* $\mathbb{R}^n$ if $f \in \mathcal{R}(I)$, and we define

$$\int_{\mathbb{R}^n} f\, dx = \int_I f\, dx.$$

Remark. The above definition is independent of the choice of I. This is because if I, I' both contain the support of f, then there exists $J \supset I \cup I'$, so that

$$\int_I f \text{ exists} \iff \int_J f \text{ exists} \iff \int_{I'} f \text{ exists} \quad \text{and} \quad \int_I f\, dx = \int_{I'} f\, dx = \int_J f\, dx.$$

[1]The *support* of f is the set on which its zero.

Lecture 20

Mar. 26 — Extending the Integral in $\mathbb{R}^n$

20.1 Extending the Riemann Integral in $\mathbb{R}^n$

Definition 20.1. If f is defined on an arbitrary set $A \subseteq \mathbb{R}^n$, define $\overline{f} : \mathbb{R}^n \to \mathbb{R}$ by zero extension, i.e.

$$\overline{f}(x) = \begin{cases} f(x) & \text{if } x \in A, \\ 0 & \text{if } x \notin A. \end{cases}$$

If the support of f is a bounded subset of $\mathbb{R}^n$, then we define the *integral of f over A* as

$$\int_A f = \int_{\mathbb{R}^n} \overline{f}.$$

Remark. We note once again that there exist functions which are not Riemann integrable on $\mathbb{R}^n$. Let A be the points in a closed interval of $\mathbb{R}^n$ with all rational coordinates. Then $f = 1$ is not integrable on A.

Remark. If A is bounded and $f = 1$, then

$$\int_A f = \int_A 1 = \operatorname{Vol}(A)$$

if 1 is integrable on A. This volume is also called the *Jordan measure* of A. The previous remark shows that not every set is Jordan measurable.

Proposition 20.1. *We have the following:*

1. *Let $A \subseteq \mathbb{R}^n$ and f, g be two integrable functions on A. Then $f + g$ is also integrable and*

$$\int_A (f+g) = \int_A f + \int_A g.$$

2. *If f is integrable on A and $c \in \mathbb{R}$, then cf is integrable on A and*

$$\int_A cf = c \int_A f.$$

3. *If $f(x) \geq 0$ on A and f is integrable, then*

$$\int_A f \geq 0.$$

4. *If $f(x) \le g(x)$ on A and f, g are integrable, then*

$$\int_A f \le \int_A g.$$

5. *If $m \le f(x) \le M$ on A and A has a volume, and f is integrable on A, then*

$$m \operatorname{Vol}(A) \le \int_A f \le M \operatorname{Vol}(A).$$

Proof. Left as an exercise. Note that the proof in the case where A is a box is already done. □

20.2 Sets of Measure Zero

Proposition 20.2. *We have the following:*

1. *A set $A \subseteq \mathbb{R}^n$ has zero volume if and only if for any $\epsilon > 0$, there exist a finite number of closed intervals in $\mathbb{R}^n$ containing A with the sum of their volumes less than ϵ.*
2. *Any subset of a subset of $\mathbb{R}^n$ of zero volume is of zero volume.*
3. *If $A \subseteq \mathbb{R}^n$ has zero volume and $B \subseteq \mathbb{R}^n$ has volume, then*

$$\operatorname{Vol}(A \cup B) = \operatorname{Vol}(B) \quad \textit{and} \quad \operatorname{Vol}(B \setminus A) = \operatorname{Vol}(B).$$

4. *The union of a finite number of zero volume sets is of zero volume.*
5. *If A has zero volume and $f : A \to \mathbb{R}$ is bounded, then f is integrable on A and*

$$\int_A f = 0.$$

6. *If $S \subseteq \mathbb{R}^{n-1}$ is compact and $f : S \to \mathbb{R}$, then the graph of f in $\mathbb{R}^n$, i.e. the set*

$$\{(x_1, \dots, x_n) \in \mathbb{R}^n : (x_1, \dots, x_{n-1}) \in S,\, x_n = f(x_1, \dots, x_{n-1})\},$$

is of zero volume.

Proof. See the textbook (Rosenlicht). □

Proposition 20.3. *Let A, B be two subsets of $\mathbb{R}^n$ such that $\operatorname{Vol}(A \cap B) = 0$ and $f : A \cup B \to \mathbb{R}$ is integrable on both A and B. Then*

$$\int_{A \cup B} f = \int_A f + \int_B f.$$

Proof. Define $f_1, f_2, f_3 : \mathbb{R}^n \to \mathbb{R}$ by

$$f_1(x) = \begin{cases} f(x) & \text{if } x \in A, \\ 0 & \text{if } x \notin A, \end{cases} \quad f_2(x) = \begin{cases} f(x) & \text{if } x \in B, \\ 0 & \text{if } x \notin B, \end{cases} \quad \text{and} \quad f_3(x) = \begin{cases} f(x) & \text{if } x \in A \cap B, \\ 0 & \text{if } x \notin A \cap B. \end{cases}$$

Then

$$\int_{\mathbb{R}^n} f_1 = \int_A f \quad \text{and} \quad \int_{\mathbb{R}^n} f_2 = \int_B f. \tag{1}$$

Since f is integrable on A and B, it must be bounded on A and B. Then

$$\int_{\mathbb{R}^n} f_3 = \int_{A\cap B} f = 0 \tag{2}$$

since $\mathrm{Vol}(A \cap B) = 0$ and f is bounded on $A \cap B$. Now if $x \in A \cup B$, then $f(x) = f_1 + f_2 - f_3$, and if $x \notin A \cup B$, then $f_1 + f_2 - f_3 = 0$. Then we get that

$$\int_{A\cup B} f = \int_{\mathbb{R}^n} (f_1 + f_2 - f_3) = \int_{\mathbb{R}^n} f_1 + \int_{\mathbb{R}^n} f_2 - \int_{\mathbb{R}^n} f_3 = \int_A f + \int_B f$$

from (1) and (2), as required. □

Corollary 20.0.1. *If A and B have volume and $A \cap B$ has zero volume, then*

$$\mathrm{Vol}(A \cup B) = \mathrm{Vol}(A) + \mathrm{Vol}(B).$$

Proof. Choose $f = 1$ in the previous proposition. □

Theorem 20.1 (Lebesgue's criterion for Riemann integrability)**.** *Let $A \subseteq \mathbb{R}^n$ be a set with volume and let $f : A \to \mathbb{R}$ be a bounded function that is continuous except on a subset of A with zero volume. Then f is integrable on A.*

Proof. First we consider the case where A is a closed interval in $\mathbb{R}^n$ and f is continuous on A. Now f is continuous on a compact set, so it is bounded, i.e. there exists $M \in \mathbb{R}$ such that $|f(x)| \leq M$ on A. Also since A is compact, in fact f is uniformly continuous on A, so for any $\epsilon > 0$, there exists $\delta > 0$ such that $|f(x) - f(y)| < \epsilon$ if $d(x, y) < \delta$. Choose a partition of $A = I$ into closed subintervals $I_1, \ldots, I_N$ such that $I = I_1 \cup I_2 \cup \cdots \cup I_N$ and $\mathrm{Vol}(I_i \cap I_j) = 0$,[1] and $d(x, y) < \delta$ if $x, y \in I_j$. Define

$$f_1(x) = \begin{cases} \min\{f(y) : y \in I_j\} & \text{if } x \in I_j \text{ and } x \notin I_k \text{ for } k \neq j \\ -M & \text{otherwise.} \end{cases}$$

Similarly define

$$f_2(x) = \begin{cases} \max\{f(y) : y \in I_j\} & \text{if } x \in I_j \text{ and } x \notin I_k \text{ for } k \neq j \\ M & \text{otherwise.} \end{cases}$$

By construction we have $f_1 \leq f \leq f_2$, and[2]

$$\int_I (f_2 - f_1) = \sum_{j=1}^{N} \int_{\mathrm{int}\, I_j} (f_2 - f_1) \leq \sum_{j=1}^{N} \epsilon \,\mathrm{Vol}(I_j) = \epsilon \,\mathrm{Vol}(I)$$

by uniform continuity. So f is integrable on A in this case. Rest of the proof for next class. □

[1] Cutting the box into little rectangles is sufficient to do this, for example.
[2] Here $\mathrm{int}\, I_j$ denotes the *interior* of I_j.

Lecture 21

Apr. 2 — Iterated Integrals

21.1 Double Integrals and Iterated Integrals

Theorem 21.1. *Suppose $f(x,y)$ is integrable on $D = [a,b] \times [c,d]$ and for each $x \in [a,b]$, $f(x,y)$ is integrable on $[c,d]$. Then*

$$\int_a^b dx \left[\int_c^d f(x,y)\,dy \right] \text{ exists} \quad \text{and} \quad \int_a^b dx \left[\int_c^d f(x,y)\,dy \right] = \iint_D f(x,y)\,dxdy$$

Proof. Divide $[a,b]$ and $[c,d]$ by $a = x_0 < x_1 < \cdots < x_n = b$ and $c = y_0 < y_1 < \cdots < y_m = d$. Take $\xi_i \in [x_{i-1}, x_i]$ and $\eta_j \in [y_{j-1}, y_j]$ for each $1 \le i \le n$ and $1 \le j \le m$. Denote

$$\Delta = \max\{\Delta x_i, \Delta y_j\}, \quad \Delta x_i = x_i - x_{i-1},\, \Delta y_j = y_j - y_{j-1}.$$

Then

$$S = \sum_{i=1}^n \sum_{j=1}^m f(\xi_i, \eta_j) \Delta x_i \Delta y_j \to \iint_D f(x,y)\,dxdy$$

as $\Delta \to 0$ since f is integrable on D. Let $\lambda_1 = \max\{\Delta x_i\}$ and $\lambda_2 = \max\{\Delta y_j\}$. Note that $\Delta \to 0$ if and only if $\lambda_1, \lambda_2 \to 0$. Then we can write

$$S = \sum_{i=1}^n \left[\sum_{j=1}^m f(\xi_i, \eta_j) \Delta y_j \right] \Delta x_i \to \sum_{i=1}^n \left[\int_c^d f(\xi_i, y)\,dy \right] \Delta x_i$$

as $\lambda_2 \to 0$ since $f(x,y)$ is integrable in y for any fixed x. Now taking $\lambda_1 \to 0$,

$$\int_a^b dx \left[\int_c^d f(x,y)\,dy \right] = \lim_{\lambda_1 \to 0} \sum_{i=1}^n \left[\int_c^d f(\xi_i, y)\,dy \right] \Delta x_i = \lim_{\Delta \to 0} S = \iint_D f(x,y)\,dxdy$$

from before. So the left-hand side integral exists and equals the double integral. □

Remark. Knowing that $f(x,y)$ is integrable on $D = [a,b] \times [c,d]$ does *not* in general imply that $f(x,y)$ is integrable on $[c,d]$ for any fixed $x \in [a,b]$.

Example 21.0.1. Let $D = [0,1] \times [0,1]$ and

$$f(x,y) = \begin{cases} 1/p & \text{if } x = r/p \text{ for } r,p \text{ coprime, } y \text{ is irrational} \\ 1/q & \text{if } y = s/q \text{ for } s,q \text{ coprime, } x \text{ is irrational} \\ 0 & \text{if } x,y \text{ are both rational or irrational.} \end{cases}$$

Observe that f is integrable on D since for any $\epsilon > 0$, $f(x,y) \geq \epsilon$ only on a finite number of straight lines. So there exists a partition such that the finite number of lines are contained in a union of small rectangular domains with area $< \epsilon$. Then the total oscillation amplitude of this partition for $f(x,y)$ is

$$\sum_{i=1}^{n} \omega_i(f)\Delta\sigma_i = \sum_{\text{oscillation} \leq \epsilon} \omega_i(f)\Delta\sigma_i + \sum_{\text{contains lines}} \omega_i(f)\Delta\sigma_i \leq \epsilon + \epsilon = 2\epsilon$$

where $\Delta\sigma_i = \Delta x_i \Delta y_i$. So $f(x,y)$ is integrable on D. Now for a fixed $x = r/p$, we have

$$f(r/p, y) = \begin{cases} 0 & \text{if } y \text{ is rational} \\ 1/p & \text{if } y \text{ is irrational.} \end{cases}$$

This function is not integrable for $y \in [0,1]$.

Corollary 21.1.1. *If f is integrable on $D = [a,b] \times [c,d]$ and for fixed $y \in [c,d]$, $f(x,y)$ is integrable on $[a,b]$. Then*

$$\iint_D f(x,y)\,dxdy = \int_c^d \left[\int_a^b f(x,y)\,dx\right] dy.$$

Proof. Repeat the same proof but start by integrating in x. □

Theorem 21.2. *Let $\varphi_1, \varphi_2 : [a,b] \to \mathbb{R}$ be continuous and define the Type I region*

$$D = \{(x,y) \in \mathbb{R}^2 : a \leq x \leq b,\ \varphi_1(x) \leq y \leq \varphi_2(x)\}.$$

Assume $f(x,y)$ is integrable on D and for each $x \in [a,b]$,

$$I(x) = \int_{\varphi_1(x)}^{\varphi_2(x)} f(x,y)\,dy$$

exists. Then

$$\iint_D f(x,y)\,dxdy = \int_a^b \left[\int_{\varphi_1(x)}^{\varphi_2(x)} f(x,y)\,dy\right] dx.$$

Proof. Let $c = \inf_{a \leq x \leq b} \varphi_1(x)$ and $d = \sup_{a \leq x \leq b} \varphi_2(x)$, so that $D \subseteq R = [a,b] \times [c,d]$. Define

$$f^*(x,y) = \begin{cases} f(x,y) & \text{if } (x,y) \in D \\ 0 & \text{if } (x,y) \in R \setminus D. \end{cases}$$

Then f^* is integrable on R and

$$\iint_R f^*(x,y)\,dxdy = \iint_D f(x,y)\,dxdy$$

since

$$\iint_R f^*(x,y)\,dxdy = \iint_D f^*(x,y)\,dxdy + \iint_{R \setminus D} f^*(x,y)\,dxdy = \iint_D f(x,y)\,dxdy.$$

since D is a measurable set. Now apply the previous theorem to f^* on R to get

$$\iint_D f(x,y)\,dxdy \iint_R f^*(x,y)\,dxdy = \int_a^b \left[\int_c^d f^*(x,y)\,dy\right] dx = \int_a^b \left[\int_{\varphi_1(x)}^{\varphi_2(x)} f(x,y)\,dy\right] dx,$$

which is the desired result. □

Corollary 21.2.1. *Let $\phi_1, \phi_2 : [c, d] \to \mathbb{R}$ be continuous and define the Type II region*

$$D = \{(x, y) \in \mathbb{R}^2 : c \leq y \leq d,\ \phi_1(y) \leq x \leq \phi_2(y)\}.$$

Assume f is integrable on D and for each $y \in [c, d]$, $f(x, y)$ is integrable on $[\phi_1(y), \phi_2(y)]$. Then

$$\iint_D f(x, y)\, dxdy = \int_c^d \left[\int_{\phi_1(y)}^{\phi_2(y)} f(x, y)\, dx\right] dy.$$

Proof. Repeat the same proof. □

21.2 Applications

Example 21.0.2. Assume $p(x)$ is integrable on $[a, b]$ and $p(x) \geq 0$, and $f(x), g(x)$ are increasing on $[a, b]$. Show

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

Proof. Let

$$\Delta = \int_a^b p(x)f(x)g(x)\, dx \int_a^b p(x)\, dx - \int_a^b p(x)f(x)\, dx \int_a^b p(x)g(x)\, dx.$$

Replace the integration variable from x to y in the two parts to get

$$\Delta = \int_a^b p(x)f(x)g(x)\, dx \int_a^b p(y)\, dy - \int_a^b p(x)f(x)\, dx \int_a^b p(y)g(y)\, dy.$$

Let $D = [a, b] \times [a, b]$, and by the previous theorem we get

$$\Delta = \iint_D [p(x)f(x)g(x)p(y) - p(x)f(x)p(y)g(y)]\, dxdy = \iint_D p(x)p(y)f(x)\,[g(x) - g(y)]\, dxdy. \quad (1)$$

By symmetry,

$$\Delta = \iint_D p(x)p(y)f(y)\,[g(y) - g(x)]\, dxdy. \quad (2)$$

also. Add (1) and (2) and divide by 2 to get

$$\Delta = \frac{1}{2}\iint_D p(x)p(y)[f(x) - f(y)][g(x) - g(y)]dxdy \geq 0$$

since $p(x) \geq 0$, and $f(x) - f(y)$ and $g(x) - g(y)$ have the same sign since f, g are increasing. □

Example 21.0.3. To compute

$$I = \int_{\mathbb{R}} e^{-x^2}\, dx,$$

we can use a similar trick and write

$$I^2 = \int_{\mathbb{R}} e^{-x^2}\, dx \int_{\mathbb{R}} e^{-y^2}\, dy = \iint_{\mathbb{R}^2} e^{-(x^2+y^2)}\, dxdy = \int_0^\infty \int_0^{2\pi} e^{-r^2} r\, d\theta dr = 2\pi \int_0^\infty e^{-r^2} r\, dr = \pi,$$

so we get that $I = \sqrt{\pi}$. Note that we get a factor for u-substitution after changing to polar coordinates.

21.3 Triple Integrals and Iterated Integrals in 3D

Theorem 21.3. *Let D be a measurable region in the xy-plane and $\varphi_1, \varphi_2 : D \to \mathbb{R}$ be continuous, and define*

$$V = \{(x, y, z) \in \mathbb{R}^3 : (x, y) \in D,\ \varphi_1(x, y) \le z \le \varphi_2(x, y)\}.$$

If $f(x, y, z)$ is integrable on V and for each $(x, y) \in D$, $f(x, y, z)$ is integrable on $[\varphi_1(x, y), \varphi_2(x, y)]$, then

$$\iiint_V f(x, y, z)\, dxdydz = \iint_D dxdy \left[\int_{\varphi_1(x,y)}^{\varphi_2(x,y)} f(x, y, z)\, dz\right].$$

Proof. Similar idea, zero-extend f to a box in $\mathbb{R}^3$ and integrate. □

Theorem 21.4. *Suppose we have $D : [c, d] \to \mathbb{R}^2$ and a region of the form*

$$V = \{(x, y, z) \in \mathbb{R}^3 : c \le z \le d,\ (x, y) \in D(z)\}.$$

If $f(x, y, z)$ is integrable on V and for each $z \in [c, d]$, $D(z)$ is measurable and $f(x, y, z)$ is integrable on $D(z)$, then

$$\iiint_V f(x, y, z)\, dxdydz = \int_c^d dz \left[\iint_{D(z)} f(x, y, z)\, dxdy\right].$$

Proof. Use a similar idea. □

Lecture 22

Apr. 4 — Change of Variables

22.1 Change of Variables for Double Integrals

Consider a region G in uv-coordinates, and define a transformation T on G to xy-coordinates by

$$T : \begin{cases} x = x(u,v) \\ y = y(u,v). \end{cases}$$

Set $\Omega = T(G)$. Assume that T is injective and $T \in C^2(\overline{G})$.

Definition 22.1. We define the *Jacobian* of T to be

$$J(u,v) = \frac{\partial(x,y)}{\partial(u,v)} = \det \begin{pmatrix} \partial x/\partial u & \partial x/\partial v \\ \partial y/\partial u & \partial y/\partial v \end{pmatrix}.$$

Remark. The Jacobian J does not change sign in G.

The goal now is to show the change of variables formula

$$\iint_\Omega f(x,y)\,dxdy = \iint_G f(x(u,v), y(u,v))|J(u,v)|\,dudv.$$

Notice the extra $|J(u,v)|$ factor on the right-hand side.

Remark. Let Γ be a closed curve in the counterclockwise orientation that encloses Ω. If Γ is piecewise continuous, then recall that by Green's theorem we have

$$\text{area}(\Omega) = \frac{1}{2}\oint_\Gamma x\,dy - y\,dx.$$

Lemma 22.1. *Let $G = (u_0, u_0 + h) \times (v_0, v_0 + h)$ be a square region for some $h > 0$. Assume T is injective and $T \in C^2(\overline{G})$. Then*[1]

$$m(TG) = \iint_G |J(u,v)|\,dudv.$$

[1]Recall that $m(TG)$ denotes the measure of TG. Also TG is the image of G under T.

Proof. When $J > 0$, $\partial(TG)$ is counterclockwise, so by the previous remark we can calculate

$$\begin{aligned}
2\,\text{area}(TG) &= \int_{u_0}^{u_0+h} \left[x(u,v_0)\frac{\partial y(u,v_0)}{\partial u} - y(u,v_0)\frac{\partial x(u,v_0)}{\partial u}\right] du \\
&\quad + \int_{v_0}^{v_0+h} \left[x(u_0+h,v)\frac{\partial y(u_0+h,v)}{\partial v} - y(u_0+h,v)\frac{\partial x(u_0+h,v)}{\partial v}\right] dv \\
&\quad + \int_{u_0+h}^{u_0} \left[x(u,v_0+h)\frac{\partial y(u,v_0+h)}{\partial u} - y(u,v_0+h)\frac{\partial x(u,v_0+h)}{\partial u}\right] du \\
&\quad + \int_{v_0+h}^{v_0} \left[x(u_0,v)\frac{\partial y(u_0,v)}{\partial v} - y(u_0,v)\frac{\partial x(u_0,v)}{\partial v}\right] dv \\
&= I + II + III + IV.
\end{aligned}$$

By the fundamental theorem of calculus, we get

$$\begin{aligned}
I &= \int_{u_0}^{u_0+h} \left[x(u,v_0+h)\frac{\partial(u,v_0+h)}{\partial u} - x(u,v_0)\frac{\partial y(u,v_0)}{\partial u}\right] du \\
&= \int_{u_0}^{u_0+h} du \left[\int_{v_0}^{v_0+h} \frac{\partial x(u,v)}{\partial v}\frac{\partial y(u,v)}{\partial u} + x(u,v)\frac{\partial^2 y(u,v)}{\partial v\partial u}\right] dv = \iint_G \left[\frac{\partial x}{\partial v}\frac{\partial y}{\partial u} + x\frac{\partial^2 y}{\partial v\partial u}\right] dudv.
\end{aligned}$$

Similarly apply this to the other three sides and combine to get (note that T is C^2 on $\overline{G}$),

$$\begin{aligned}
2\,\text{area}(TG) &= \iint_G \left[\frac{\partial x}{\partial u}\frac{\partial y}{\partial v} + x\frac{\partial^2 y}{\partial u\partial v}\right] dudv - \iint_G \left[\frac{\partial x}{\partial v}\frac{\partial y}{\partial u} + x\frac{\partial^2 y}{\partial v\partial u}\right] dudv \\
&\quad + \iint_G \left[\frac{\partial y}{\partial v}\frac{\partial x}{\partial u} + y\frac{\partial^2 x}{\partial v\partial u}\right] dudv - \iint_G \left[\frac{\partial y}{\partial u}\frac{\partial x}{\partial v} + y\frac{\partial^2 x}{\partial u\partial v}\right] dudv \\
&= 2\iint_G \left(\frac{\partial x}{\partial u}\frac{\partial y}{\partial v} - \frac{\partial x}{\partial v}\frac{\partial y}{\partial u}\right) = 2\iint_G J(u,v)\,dudv,
\end{aligned}$$

which is the desired result. The absolute value of J is necessary when $J < 0$, since $\partial(TG)$ is clockwise. □

Theorem 22.1. *Let $T : G \to \Omega$, where G and Ω are both measurable sets in $\mathbb{R}^2$. Suppose T is bijective and $T \in \mathbb{C}^2(\overline{G})$, (and that $J(u,v) \neq 0$ in G).*[2] *If $f(x,y)$ is integrable on $\overline{\Omega}$, then*

$$\iint_\Omega f(x,y)\,dxdy = \iint_G f(x(u,v),y(u,v))|J(u,v)|\,dudv.$$

Proof. Use parallel lines with distance h to cut G into small "rectangular" (except near the boundary) sets $\Delta\sigma_i$. Let

$$\Delta = \{\underbrace{\Delta\sigma_1, \Delta\sigma_2, \ldots, \Delta\sigma_n}_{\text{contained in int}\,G}, \underbrace{\Delta\sigma_{n+1}, \ldots, \Delta\sigma_{n+p}}_{\text{intersects with }\partial G}\}.$$

Let $(u_i, v_i) \in \Delta\sigma_i$ with $1 \le i \le n$. Then $T : \Delta\sigma_i \to T(\Delta\sigma_i)$, so that $x_i = x(u_i,v_i)$ and $y_i = y(u_i,v_i)$. By the lemma,

$$m(T(\Delta\sigma_i)) = \iint_{\Delta\sigma_i} |J(u,v)|\,dudv = |J(\overline{u}_i,\overline{v}_i)|m(\Delta\sigma_i) = h^2|J(\overline{u}_i,\overline{v}_i)|.$$

[2]This last condition is implied by the previous two.

for some $(\overline{u}_i, \overline{v}_i) \in \Delta\sigma_i$ by the middle value theorem (also note that $m(\Delta\sigma_i) = h^2$). So if f is continuous on G, then

$$\iint_G f\, dxdy = f(\xi)m(G)$$

where ξ is some point in $\overline{G}$. Now consider a limit of the Riemann sums. We have

$$\lim_{h\to 0}\sum_{i=1}^{n} f(x(u_i,v_i), y(u_i,v_i))\underbrace{|J(\overline{u}_i,\overline{v}_i)|m(\Delta\sigma_i)}_{=m(T(\Delta\sigma_i))} = \iint_\Omega f(x,y)\, dxdy$$

since for the sets near the boundary,

$$\lim_{h\to 0}\sum_{i=n+1}^{n+p} m(T(\Delta\sigma_i)) = 0 \implies \lim_{h\to 0}\sum_{i=n+1}^{n+p} f(x_i,y_i)m(T(\Delta\sigma_i)) = 0.$$

and f is integrable and thus bounded on $\overline{\Omega}$. Now if $J(\overline{u}_i,\overline{v}_i) \to J(u_i,v_i)$, then

$$\sum_{i=1}^{n} f(x(u_i,v_i), y(u_i,v_i))|J(u_i,v_i)|m(\Delta\sigma_i) \to \iint_G f(x(u,v),y(u,v))|J(u,v)|\, dudv$$

as $h \to 0$. To see that $J(\overline{u}_i,\overline{v}_i) \to J(u_i,v_i)$, observe that for any $\epsilon > 0$, since $|J(u,v)|$ is uniformly continuous on $\overline{G}$, there exists $\delta > 0$ such that

$$d((u_i,v_i),(\overline{u}_i,\overline{v}_i)) < \delta \implies ||J(u_i,v_i)| - |J(\overline{u}_i,\overline{v}_i)|| < \frac{\epsilon}{M\cdot m(G)},$$

where $|f| \le M$ on $\overline{G}$. So if $h < \delta/\sqrt{2}$, then we have

$$\left|\sum_{i=1}^{n} f(x_i,y_i)|J(\overline{u}_i,\overline{v}_i)|m(\Delta\sigma_i) - \sum_{i=1}^{n} f(x_i,y_i)|J(u_i,v_i)|m(\Delta\sigma_i)\right| \le \frac{\epsilon}{M\cdot m(G)}\cdot M\cdot m(G) = \epsilon.$$

This finishes the desired result. □

Remark. The theorem actually also holds for $T \in C^1(\overline{G})$. This is because if

$$\iint_G f(x(u,v),y(u,v))|J(u,v)|\, dudv = \iint_\Omega f(x,y)\, dxdy$$

for any $T \in C^2$, then we can choose $T^n \in C^2$ such that $|T_n - T|_{C^1} \to 0$. Then we have

$$\iint_G f(x_n(u,v),y_n(u,v))|J_n(u,v)|\, dudv = \iint_{T_n(G)} f(x,y)\, dxdy.$$

As $n \to \infty$, we have $T_n(G) \to T(G) = \Omega$, so that

$$\text{LHS} \to \iint_G f(x(u,v),y(u,v))|J(u,v)|\, dudv \quad \text{and} \quad \text{RHS} \to \iint_\Omega f(x,y)\, dxdy$$

since we have uniform convergence.

22.2 Change of Variables in 3D

Let G be a measurable set in $\mathbb{R}^3$ with uvw-coordinates and

$$T : \begin{cases} x = x(u,v,w) \\ y = y(u,v,w) \\ z = z(u,v,w) \end{cases} .$$

Set $D = T(G)$. Assume that T is a homeomorphism and $T \in C^1(\overline{G})$. Then define

$$J(u,v,w) = \frac{\partial(x,y,z)}{\partial(u,v,w)} = \det \begin{pmatrix} \partial x/\partial u & \partial x/\partial v & \partial x/\partial w \\ \partial y/\partial u & \partial y/\partial v & \partial y/\partial w \\ \partial z/\partial u & \partial z/\partial v & \partial z/\partial w \end{pmatrix} .$$

If f is integrable on $\overline{D}$, then

$$\iiint_D f(x,y,z)\, dxdydz = \iiint_G f(x(u,v,w), y(u,v,w), z(u,v,w))|J(u,v,w)|\, dudvdw.$$

The proof is similar to the 2D case (get a formula for the cube and proceed similarly).

Lecture 23

Apr. 9 — Change of Variables, Part 2

23.1 Change of Variables Examples

Example 23.0.1. Compute

$$I = \iint_D \sqrt{\sqrt{x} + \sqrt{y}}\, dxdy$$

where D is enclosed by $C : \sqrt{x} + \sqrt{y} = 1$ and the coordinate axes.

Proof. We would like $C : x = \cos^4 t, y = \sin^4 t$ for $0 \le t \le \pi/2$. So let

$$T : \begin{cases} x = r\cos^4 t, & 0 \le r \le 1 \\ y = r\sin^4 t, & 0 \le t \le \pi/2. \end{cases}$$

This gives $T : [0,1] \times [0, \pi/2] \to D$ which sends $(r,t) \to (x,y)$. Then

$$J(r,t) = \det \begin{pmatrix} \partial x/\partial r & \partial x/\partial t \\ \partial y/\partial r & \partial y/\partial t \end{pmatrix} = 4r\cos^3 t \sin^3 t.$$

Now making the change of variables in the integral gives

$$I = \int_0^{\pi/2} \int_0^1 r^{1/4} 4r \cos^3 t \sin^3 t \, drdt = \int_0^1 4r^{5/4}\, dr \int_0^{\pi/2} \cos^3 t \sin^3 t\, dt = \frac{2}{15}.$$

The latter integral can be calculated by writing $\sin^2 t = 1 - \cos^2 t$ and using the substitution $u = \cos t$. $\square$

Example 23.0.2. Let $h = \sqrt{\alpha^2 + \beta^2 + \gamma^2} > 0$ and f be continuous on $[-h, h]$. Show that

$$\iiint_V f(\alpha x + \beta y + \gamma z)\, dxdydz = \pi \int_{-1}^1 (1 - \zeta^2) f(h\zeta)\, d\zeta,$$

where $V : x^2 + y^2 + z^2 \le 1$.

Proof. Setting $\alpha x + \beta y + \gamma z = 0$ defines a plane passing through the origin in $\mathbb{R}^2$. Choose the ζ-axis to be normal to this plane, and let ξ, η be two orthogonal axes on the plane. Define the coordinate transformation $T^{-1} : (\xi, \eta, \zeta) \to (x, y, z)$ be given by

$$\begin{cases} \xi = a_1 x + b_1 y + c_1 z \\ \eta = a_2 x + b_2 y + c_2 z \\ \zeta = (\alpha x + \beta y + \gamma z)/h, \end{cases}$$

where $\{(a_1, b_1, c_1)^T, (a_2, b_2, c_2)^T\}$ is an orthonormal basis for the plane. Note that $(\alpha, \beta, \gamma)^T$ is the normal vector of the plane. Then

$$\frac{\partial(\xi,\eta,\zeta)}{\partial(x,y,z)} = \det\begin{pmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ \alpha/h & \beta/h & \gamma/h \end{pmatrix} = 1$$

since this matrix is orthogonal and preserves orientation by construction. This gives

$$J(\xi,\eta,\zeta) = \frac{\partial(x,y,z)}{\partial(\xi,\eta,\zeta)} = \left(\frac{\partial(\xi,\eta,\zeta)}{\partial(x,y,z)}\right)^{-1} = 1.$$

Now under the transformation T^{-1}, we have

$$V : \{x^2+y^2+z^2 \le 1\} \xrightarrow{T^{-1}} G : \{\xi^2+\eta^2+\zeta^2 \le 1\}.$$

Substituting this into the integral, we get

$$\begin{aligned}\iiint_V f(\alpha x+\beta y+\gamma z)\,dxdydz &= \iiint_{\xi^2+\eta^2+\zeta^2\le 1} f(h\zeta)\,d\xi d\eta d\zeta \\ &= \int_{-1}^{1} d\zeta \iint_{\xi^2+\eta^2\le 1-\zeta^2} f(h\zeta)\,d\xi d\eta = \int_{-1}^{1} f(h\zeta)\pi(1-\zeta^2)\,d\zeta,\end{aligned}$$

which is the desired result. □

23.2 The Cylindrical and Spherical Coordinate Systems

The *cylindrical* coordinate system is the change of variables $(x,y,z) \to (r,\theta,z)$ given by

$$\begin{cases} x = r\cos\theta \\ y = r\sin\theta \\ z = z \end{cases} \quad \text{with } J(r,\theta,z) = r.$$

The *spherical* coordinate system is the change of variables $(x,y,z) \to (r,\varphi,\theta)$ given by

$$\begin{cases} x = r\sin\varphi\cos\theta \\ y = r\sin\varphi\sin\theta \\ z = r\cos\varphi \end{cases} \quad \text{with } J(r,\varphi,\theta) = r^2\sin\varphi.$$

For spherical coordinates we have $r \ge 0$, $0 \le \varphi \le \pi$, and $0 \le \theta \le 2\pi$.

Example 23.0.3. Find

$$\iiint_V (x^2+y^2+z^2)\,dxdydz$$

where $V : x^2/a^2 + y^2/b^2 + z^2/c^2 \le 1$.

Proof. Define the transformation

$$T : \begin{cases} x = ar\sin\varphi\cos\theta \\ y = br\sin\varphi\sin\theta \\ z = cr\cos\varphi. \end{cases}$$

Then we have

$$\frac{\partial(x,y,z)}{\partial(r,\varphi,\theta)} = abcr^2\sin\varphi.$$

Making the substitution, this gives

$$\begin{aligned}
&\iiint_V (x^2+y^2+z^2)\,dxdydz \\
&\quad = \int_0^{2\pi} d\theta \int_0^{\pi} d\varphi \int_0^1 (a^2\sin^2\varphi\cos^2\theta + b^2\sin^2\varphi\sin^2\theta + c^2\cos^2\varphi)abcr^4\sin\varphi\,dr \\
&\quad = \frac{4}{15}abc(a^2+b^2+c^2)\pi
\end{aligned}$$

as the desired result. □

23.3 More Change of Variables Examples

Example 23.0.4. Find

$$I = \int_0^\infty \frac{e^{-ax}-e^{-bx}}{x}\,dx$$

for $a, b > 0$.

Proof. First observe that for fixed $x > 0$, we can write

$$\frac{e^{-ax}-e^{-bx}}{x} = -\frac{e^{-yx}}{x}\Big|_{y=a}^{y=b} = \int_a^b \frac{d}{dy}\left(-\frac{e^{-yx}}{x}\right)dy = \int_a^b e^{-xy}\,dy$$

by the fundamental theorem of calculus. This then gives

$$I = \int_0^\infty dx\int_a^b e^{-xy}\,dy = \lim_{T\to\infty}\int_0^T dx\int_a^b e^{-xy}\,dy$$

For the latter integral, we can switch the order of integration to get

$$\begin{aligned}
\int_0^T dx\int_a^b e^{-xy}\,dy &= \int_a^b dy\int_0^T e^{-xy}\,dx = \int_a^b dy\left[-\frac{e^{-xy}}{y}\right]_{x=0}^{x=T} = \int_a^b \frac{1-e^{-Ty}}{y}\,dy \\
&= \int_a^b \frac{1}{y}\,dy - \int_a^b \frac{e^{-Ty}}{y}\,dy = \ln(b/a) - \int_{Ta} Tb\frac{e^{-Ty'}}{y'}\,dy',
\end{aligned}$$

where $y' = Ty$. Letting $T \to \infty$, we have

$$I = \lim_{T\to\infty}\int_0^T dx\int_a^b e^{-xy}\,dy = \ln(b/a) - \lim_{T\to\infty}\int_{Ta}^{Tb}\frac{e^{-Ty'}}{y'}\,dy' = \ln(b/a) \qquad (*)$$

since

$$\int_1^\infty \frac{e^{-y}}{y}\,dy \text{ converges} \quad \text{and} \quad h(A) = \int_0^A \frac{e^{-y}}{y}\,dy \text{ is Cauchy in } A,$$

so that the latter integral in $(*)$ vanishes as $T \to \infty$. □

Remark. We might have been able to just switch orders at the very beginning with the improper integral, but we need to argue uniform convergence so that the exchange is permissible.

Exercise 23.1. Let f be differentiable on $(0, \infty)$ and suppose that

$$\int_1^\infty \frac{f(t)}{t}\,dt$$

exists. Then for $a, b > 0$, show that

$$I = \int_0^\infty \frac{f(ax) - f(bx)}{x}\,dx = f(0)\ln(b/a).$$

Remark. The previous example is a special case of this exercise, with $f(x) = e^{-x}$.

Lecture 24

Apr. 11 — Green's Theorem

24.1 Midterm 2 Problems

The following was Problem 3 on Midterm 2:

Exercise 24.1. For a given function $y(t) \in C[0,1]$ (i.e. continuous functions in $[0,1]$) and a constant $\lambda \in \mathbb{R}$ with $|\lambda| < 1$, show that the integral equation

$$x(t) - \lambda \int_0^1 e^{t-s} x(s)\, ds = y(t) \tag{$*$}$$

has a unique solution $x(t) \in C[0,1]$.

Remark. A common idea was to define

$$T : x(t) \mapsto y(t) + \lambda \int_0^1 e^{t-s} x(s)\, ds.$$

and $\rho(u,v) = \sup_{t\in[0,1]} |u(t) - v(t)|$. But we run into problems since

$$\rho(Tu, Tv) \leq |\lambda| \sup_{t\in[0,1]} \left| \int_0^1 e^{t-s}(u(s) - v(s))\, ds \right| \leq |\lambda| \rho(u,v) \sup_{t\in[0,1]} e^t \int_0^1 e^{-s}\, ds$$

But $\sup_{t\in[0,1]} e^t = e$ and the integral evaluates to $1 - e^{-1}$, so we have

$$\rho(Tu, Tv) \leq |\lambda| e(1 - e^{-1}) \rho(u,v) \leq |\lambda|(1-e)\rho(u,v).$$

This doesn't work since $(1-e) > 1$.

Proof. A better idea is to first transform $(*)$ by multiplying by e^{-t}:

$$e^{-t} x(t) - \lambda \int_0^1 e^{-s} x(s)\, ds = e^{-t} y(t)$$

since t is independent of the integral. Then set $z(t) = e^{-t} x(t)$ and define

$$T : z(t) \mapsto e^{-t} y(t) + \lambda \int_0^1 z(s)\, ds.$$

Using this we can get

$$d(Tu, Tv) = \lambda \sup_{t\in[0,1]} \left| \int_0^1 u(s) - v(s)\, ds \right| \leq \lambda \rho(u,v),$$

which is good enough. Then by the contraction mapping principle, T has a unique fixed point, and multiplying by e^t gives a unique solution to $(*)$. $\square$

24.2 Green's Theorem

Theorem 24.1 (Green's theorem). *Let D be a region in $\mathbb{R}^2$ enclosed by a finite number of measurable curves, and $P(x,y), Q(x,y)$ be continuous on D with continuous partial derivatives. Then*

$$\int_{\partial D} P\,dx + Q\,dy = \iint_D \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right) dxdy. \tag{$*$}$$

Here ∂D is oriented so that $\{\vec{n}, \vec{\tau}\}$ is a right-handed coordinate system, where $\vec{n}$ is the outward normal to the region and $\vec{\tau}$ is the tangent vector of the curve ∂D.[1]

Proof. First we consider Type I domains, i.e. regions of the form

$$D = \{a \le x \le b,\, \varphi(x) \le y \le \psi(x)\}.$$

Let A, B, C, D be the four vertices of the region D, going counterclockwise and starting in the bottom-left, i.e. we have

$$A = (a, \varphi(a)),\ B = (b, \varphi(b)),\ C = (b, \psi(b)),\ D = (a, \psi(a)).$$

Then

$$\int_{\widetilde{AB}} P\,dx = \int_a^b P(x, \varphi(x))\,dx, \quad \int_{\widetilde{CD}} P\,dx = -\int_a^b P(x, \psi(x))\,dx,$$

and

$$\int_{\widetilde{BC}} P\,dx = \int_{\widetilde{DA}} P\,dx = 0$$

since x is constant on $\widetilde{BC}$ and $\widetilde{DA}$. Thus

$$\int_{\partial D} P\,dx = \int_a^b P(x, \varphi(x))\,dx - \int_a^b P(x, \psi(x))\,dx = \int_a^b [P(x, \varphi(x)) - P(x, \psi(x))]\,dx.$$

By the fundamental theorem of calculus, we have

$$P(x, \varphi(x)) - P(x, \psi(x)) = -\int_{\varphi(x)}^{\psi(x)} \frac{\partial P}{\partial y}(x,y)\,dy,$$

so that

$$\int_{\partial D} P\,dx = -\int_a^b \int_{\varphi(x)}^{\psi(x)} \frac{\partial P}{\partial y}(x,y)\,dydx = -\iint_D \frac{\partial P}{\partial y}\,dxdy.$$

For Type II domains, i.e. regions of the form

$$D = \{c \le y \le d, \varphi(y) \le x \le \psi(y)\}.$$

Using an identical argument,

$$\int_{\partial D} Q\,dy = \iint_D \frac{\partial Q}{\partial x}\,dxdy.$$

Now if D is of both Type I and Type II, then we have both identities

$$\int_{\partial D} P\,dx = -\iint_D \frac{\partial P}{\partial y}\,dxdy \quad \text{and} \quad \int_{\partial D} Q\,dy = \iint_D \frac{\partial Q}{\partial x}\,dxdy,$$

[1] In other words, the curve ∂D is oriented so that the region D is to its *left*.

and adding the two gives

$$\int_{\partial D} P\,dx + Q\,dy = \iint_D \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right) dxdy,$$

which is precisely Green's theorem for this special type of region.

Now let D be a simply connected (i.e. no holes[2]) domain enclosed by a measurable curve. Then D can be domain enclosed by a measurable curve. Then we try to divide D by using parallel lines into $D_1, \ldots, D_n$ such that each $D_1, \ldots, D_n$ is of both Type I and Type II. Each subdomain falls into the previous case, so

$$\sum_{i=1}^{n} \int_{\partial D_i} P\,dx + Q\,dy = \sum_{i=1}^{n} \iint_{D_i} \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right) dxdy = \iint_D \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right) dxdy.$$

Now notice that each inner part of the ∂D_i is traversed twice since it is part of the boundary of two D_i, so these cancel and we get

$$\int_{\partial D} P\,dx + Q\,dy = \sum_{i=1}^{n} \int_{\partial D_i} P\,dx + Q\,dy = \iint_D \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right) dxdy,$$

which is Green's theorem for a simply connected domain.

In the most general case, divide D into a finite number of simply connected domains, and apply the previous case to each one. We still get cancellation of the inner parts of the boundaries. □

[2]More formally, D is *simply connected* if it is path-connected and every loop can be contracted to a point.

Lecture 25

Apr. 16 — The Divergence Theorem

25.1 Green's Theorem for Flux

Remark. For the orientation of the curve ∂D, we can also think of defining the tangent direction $\vec{\tau}$ by rotating the outward normal $\vec{n}$ by 90° counterclockwise.

Remark. Another notation for line integrals is to set $\vec{v} = \langle P, Q \rangle$ and write

$$\int_C P\,dx + Q\,dy = \int_C \vec{v} \cdot ds = \int_C \vec{v} \cdot \vec{\tau}\,d\ell.$$

Here $\vec{v} = \langle P, Q \rangle$ is called a *vector field*.

Corollary 25.0.1 (Green's theorem for flux)**.** *Assume the same hypotheses as in Green's theorem. Then*

$$\iint_D \left(\frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} \right) dxdy = \iint_{\partial D} \langle P, Q \rangle \cdot \vec{n}\,d\ell,$$

where $\vec{n}$ is the outward normal vector to D.

Proof. Set $P \to -Q$ and $Q \to P$ in the original statement of Green's theorem to get

$$\iint_D \left(\frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} \right) dxdy = \int_{\partial D} -Q\,dx + P\,dy = \iint_{\partial D} \langle -Q, P \rangle \cdot ds = \iint_{\partial D} \langle -Q, P \rangle \cdot \vec{\tau}\,d\ell.$$

Now observe that $\langle -Q, P \rangle$ is $\langle P, Q \rangle$ rotated 90° clockwise, so that $\langle -Q, P \rangle \cdot \vec{\tau} = \langle P, Q \rangle \cdot \vec{n}$. $\square$

25.2 An Application of Green's Theorem

Example 25.0.1. Let C be a measurable closed curve enclosing the origin. Show that

$$I = \int_C \frac{x\,dy - y\,dx}{x^2 + y^2} = 2\pi.$$

Proof. Set

$$P = -\frac{y}{x^2 + y^2} \quad \text{and} \quad Q = \frac{x}{x^2 + y^2}.$$

Since P, Q have singularities at the origin, let $C_\epsilon = \{x^2 + y^2 = \epsilon^2\}$ be a circle of radius ϵ for ϵ small. Let

$$D_\epsilon = D \setminus B_\epsilon,$$

where D is the region enclosed by C and $B_\epsilon = \{x^2+y^2 \le \epsilon^2\}$. Then by Green's theorem, we have

$$\int_{\partial D_\epsilon} \frac{x\,dy - y\,dx}{x^2+y^2} = \iint_{D_\epsilon} \underbrace{\left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right)}_{=0} dxdy = 0.$$

Now observe

$$\int_{\partial D_\epsilon} \frac{x\,dy - y\,dx}{x^2+y^2} = \int_C \frac{x\,dy - y\,dx}{x^2+y^2} - \int_{C_\epsilon} \frac{x\,dy - y\,dx}{x^2+y^2},$$

where C and C_ϵ is oriented counterclockwise. This gives

$$\int_C \frac{x\,dy - y\,dx}{x^2+y^2} = \int_{C_\epsilon} \frac{x\,dy - y\,dx}{x^2+y^2}.$$

Now parametrize C_ϵ by $x = \epsilon\cos t$ and $y = \epsilon \sin t$ for $0 \le t \le 2\pi$. Then

$$\int_{C_\epsilon} \frac{x\,dy - y\,dx}{x^2+y^2} = \int_0^{2\pi} \frac{\epsilon\cos t\cdot\epsilon\cos t - \epsilon\sin t\cdot(-\epsilon\sin t)}{\epsilon^2}\,dt = \int_0^{2\pi} 1\,dt = 2\pi,$$

which is the desired result. □

25.3 The Divergence Theorem

Remark. The divergence theorem is also sometimes called *Gauss's formula*.

Remark. Recall that for a surface $S : z = f(x, y)$. This is called the *graph* of f and we have

$$\vec{n} = \frac{1}{\sqrt{1+f_x^2+f_y^2}}\langle -f_x, -f_y, 1\rangle.$$

Then we get

$$\iint_S \vec{v}\cdot\vec{n}\,dS = \iint_S \vec{v}\cdot\langle -f_x, -f_y, 1\rangle\,dxdy,$$

where $dS = \sqrt{1+f_x^2+f_y^2}\,dxdy$.

Theorem 25.1 (Divergence theorem)**.** *Let D be a bounded region in $\mathbb{R}^3$ enclosed by a finite number of piecewise smooth orientable surfaces.*[1] *Suppose we have a vector field $\vec{v} = \langle P, Q, R\rangle$ that is continuous with continuous partial derivatives in D. Then*

$$\iiint_D \nabla\cdot\vec{v}\,dxdydz = \iiint_D \left(\frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} + \frac{\partial R}{\partial z}\right) dxdydz = \iint_{\partial D} \vec{v}\cdot\vec{n}\,dS,$$

where $\vec{n}$ is the outward normal vector to D.

Proof. First consider Type I solids of the form

$$D = \{(x,y)\in\Omega,\ \varphi(x,y) \le z \le \psi(x,y)\}$$

[1] A surface is *orientable* if it has a consistent (and continuous) choice of normal vector everywhere on the surface. The *Möbius strip* is an example of a non-orientable surface.

and let $\vec{v} = \langle 0, 0, R\rangle$. In this case we wish to show that

$$\iiint_D \frac{\partial R}{\partial z}\, dxdydz = \iint_{\partial D} \vec{v}\cdot\vec{n}\, dS,$$

where we note that $\nabla\cdot\vec{v} = \partial R/\partial z$. Now let $\partial D = S_1 \cup S_2 \cup S_3$ where

$$\begin{aligned} S_1 &= \{z = \psi(x,y),\ (x,y)\in\Omega\},\\ S_2 &= \{z = \varphi(x,y),\ (x,y)\in\Omega\},\\ S_3 &= \{(x,y)\in\partial\Omega,\ \varphi(x,y)\le z\le\psi(x,y)\}. \end{aligned}$$

Note that $\vec{n}$ is upwards on S_1, downwards on S_2, and outwards radially on S_3. Then

$$\iint_{S_3} \vec{v}\cdot\vec{n}\, dS = 0$$

since $\vec{v}\perp\vec{n}$ on S_3. So we get that

$$\begin{aligned} \iint_{\partial D} \vec{v}\cdot\vec{n}\, dS &= \iint_{S_1} \vec{v}\cdot\vec{n}\, dS + \iint_{S_2} \vec{v}\cdot\vec{n}\, dS\\ &= \iint_{\Omega} R(x,y,\psi(x,y))\, dxdy - \iint_{\Omega} R(x,y,\varphi(x,y))\, dxdy\\ &= \iint_D \left[\int_{\varphi(x,y)}^{\psi(x,y)} \frac{\partial R}{\partial z}\, dz\right] dxdy = \iiint_D \frac{\partial R}{\partial z}\, dxdydz \end{aligned}$$

by the fundamental theorem of calculus. This is the desired result in this case where D is a Type I solid. Also note that similar results hold for Type II solids of the form (set $\vec{v} = \langle 0, Q, 0\rangle$)

$$D = \{(x,z)\in\Omega,\ \varphi(x,z)\le y\le\psi(x,z)\} \implies \iiint_D \frac{\partial Q}{\partial y}\, dxdydz = \iint_{\partial D} \vec{v}\cdot\vec{n}\, dS$$

and Type III solids of the form (set $\vec{v} = \langle P, 0, 0\rangle$)

$$D = \{(y,z)\in\Omega,\ \varphi(y,z)\le x\le\psi(y,z)\} \implies \iiint_D \frac{\partial P}{\partial x}\, dxdydz = \iint_{\partial D} \vec{v}\cdot\vec{n}\, dS.$$

The proofs follow similarly as in the Type I solid case.

Now if a solid D is of all three types, then for any vector field $\vec{v} = \langle P, Q, R\rangle$, we can write

$$\vec{v} = \vec{v}_1 + \vec{v}_2 + \vec{v}_3 = \langle 0,0,R\rangle + \langle 0,Q,0\rangle + \langle P,0,0\rangle.$$

Now since D is of all three types, we can apply the previous special cases to get

$$\iiint_D \nabla\cdot\vec{v}\, dxdydz = \sum_{i=1}^{3} \iiint_D \nabla\cdot\vec{v}_i\, dxdydz = \sum_{i=1}^{3} \iint_{\partial D} \vec{v}_i\cdot n\, dS = \iint_{\partial D} \vec{v}\cdot\vec{n}\, dS.$$

This verifies the divergence theorem in this case where D is of all three types.

Now check the case where D is a tetrahedron and $\vec{v}$ is arbitrary. For each component of $\vec{v}$, project into the corresponding plane to break D into pieces of a specific type of solid. Then apply the special cases we had before. Note the cancellation on inner surface pieces. We can also get a similar result for polyhedra in general by breaking them into tetrahedra and applying the tetrahedron case.

Now for a general solid, approximate it by polyhedra and apply the previous cases. □

Remark. This is a three-dimensional generalization of the flux version of Green's theorem.

Lecture 26

Apr. 18 — Stokes's Theorem

26.1 Stokes's Theorem

Definition 26.1. The *curl* of a vector field $\vec{v} = \langle P, Q, R\rangle$, denoted $\operatorname{curl}\vec{v}$ or $\nabla \times \vec{v}$, is

$$\begin{vmatrix} i & j & k \\ \partial_x & \partial_y & \partial_z \\ P & Q & R \end{vmatrix} = \langle \partial_y R - \partial_z Q, \partial_z P - \partial_x R, \partial_x Q - \partial_y P\rangle.$$

Theorem 26.1. *Let B be a smooth surface in $\mathbb{R}^3$ and ∂B consist of a finite number of continuous curves such that the orientation of ∂B and $\vec{n}$ satisfy the right hand rule. Then for $\vec{v} = \langle P, Q, R\rangle \in C^1(B)$,*

$$\int_{\partial B} \vec{v} \cdot ds = \iint_B (\nabla \times \vec{v}) \cdot \vec{n}\, dS.$$

Proof. First suppose B is a graph surface, i.e. $z = f(x, y)$ for $(x, y) \in D$. Assume that $f \in C^1(D)$ and $\vec{v} = \langle P, 0, 0\rangle$. Then by Green's theorem, we have

$$\begin{aligned} \text{LHS} = \int_{\partial B} P(x,y,z)\, dx = \int_{\partial D} P(x, y, f(x, y))\, dx &= -\iint_D \frac{\partial}{\partial y} P(x, y, f(x, y))\, dxdy \\ &= -\iint_D \left(\frac{\partial P}{\partial y} + \frac{\partial P}{\partial z}\frac{\partial f}{\partial y}\right) dxdy. \end{aligned}$$

Now for the right hand side,

$$\nabla \times \vec{v} = \langle 0, \partial_z P, -\partial_y P\rangle,$$

so that

$$\iint_B (\nabla \times \vec{v}) \cdot \vec{n}\, dS = \iint_D (\nabla \times \vec{v}) \cdot \langle -f_x, -f_y, 1\rangle\, dxdy = \iint_D (-\partial_z P f_y - \partial_y P)\, dxdy.$$

Comparing this with the LHS, we see that the two agree and thus the theorem holds in this case. Observe that applying the same argument when $\vec{v} = \langle 0, Q, 0\rangle$ gives the similar result that

$$\int_{\partial B} Q\, dy = \iint_B (\nabla \times \vec{v}) \cdot \vec{n}\, dS,$$

where $\nabla \times \vec{v} = \langle -\partial_z Q, 0, \partial_x Q\rangle$. Now if B is a graph surface of the form $x = f(y, z)$ for $(y, z) \in D$, then for $\vec{v}_1 = \langle 0, Q, 0\rangle$ and $\vec{v}_2 = \langle 0, 0, R\rangle$, we have

$$\int_{\partial B} Q\, dy = \iint_B (\nabla \times \vec{v}_1) \cdot \vec{n}\, dS \quad \text{and} \quad \int_{\partial B} R\, dz = \iint_B (\nabla \times \vec{v}_2) \cdot \vec{n}\, dS.$$

Similarly if B is a graph surface of the form $y = f(z,x)$ for $(z,x) \in D$, then for $\vec{v}_1 = \langle 0, 0, R\rangle$ and $\vec{v}_2 = \langle P, 0, 0\rangle$, we have

$$\int_{\partial B} R\,dz = \iint_B (\nabla \times \vec{v}_1) \cdot \vec{n}\,dS \quad \text{and} \quad \int_{\partial B} P\,dx = \iint_B (\nabla \times \vec{v}_2) \cdot \vec{n}\,dS.$$

The proofs for these special cases are identical to the first.

Now if B is a triangle in $\mathbb{R}^3$, then B is of all three of the previous types. So for $\vec{v} = \langle P, Q, R\rangle$, we have

$$\int_{\partial B} P\,dx + Q\,dy + R\,dz = \iint_B (\nabla \times \vec{v}) \cdot \vec{n}\,dS,$$

which follows by breaking $\vec{v}$ into its components and applying the previous cases on each component.

For a general surface B, use a union of polygons to approximate B, and furthermore each polygon can be broken down into triangles. So we can approximate the surface by triangles. Then since Stokes's theorem holds for triangles, apply this to each triangle and note the internal edges cancel out. Now taking the limit to approach B and ∂B, we get Stokes's theorem for general surfaces. $\square$

Remark. Green's theorem is a special case of Stokes's theorem when the surface lies in the xy-plane. Here $\vec{n} = \vec{k}$ and $\vec{v} = \langle P, Q, 0\rangle$, so

$$\nabla \times \vec{v} = (\partial_x Q - \partial_y P)\vec{k},$$

which gives

$$(\nabla \times \vec{v}) \cdot \vec{n} = (\partial_x Q - \partial_y P)\vec{k} \cdot \vec{k} = \partial_x Q - \partial_y P,$$

which is precisely the integrand in the statement of Green's theorem.

26.2 The Generalized Stokes's Theorem

The generalized Stokes's theorem is a generalization of Stokes's theorem to *differential forms* on *manifolds*. Letting $\omega = P\,dx + Q\,dy + R\,dz$ be a 1-form on $\mathbb{R}^3$, we can write

$$\int_{\partial B} \omega = \int_B d\omega,$$

where $d\omega$ is the *exterior derivative* of ω, given by

$$\begin{aligned} d\omega &= \left(\frac{\partial P}{\partial x}\,dx + \frac{\partial P}{\partial y}\,dy + \frac{\partial P}{\partial z}\,dz\right) \wedge dx + \left(\frac{\partial Q}{\partial x}\,dx + \frac{\partial Q}{\partial y}\,dy + \frac{\partial Q}{\partial z}\,dz\right) \wedge dy \\ &\qquad + \left(\frac{\partial R}{\partial x}\,dx + \frac{\partial R}{\partial y}\,dy + \frac{\partial R}{\partial z}\,dz\right) \wedge dz \\ &= \left(-\frac{\partial P}{\partial y} + \frac{\partial Q}{\partial x}\right) dx \wedge dy + \left(\frac{\partial P}{\partial z} - \frac{\partial R}{\partial x}\right) dz \wedge dx + \left(\frac{\partial Q}{\partial z} - \frac{\partial R}{\partial y}\right) dz \wedge dy. \end{aligned}$$

Note that the *wedge product* $\wedge$ is alternating and multilinear, so that $dx \wedge dx = 0$ and $dx \wedge dy = -dy \wedge dx$. Here $d\omega$ is a 2-form,[1] and we can integrate 2-forms by writing

$$u_1\,dy \wedge dz + u_2\,dz \wedge dx + u_3\,dx \wedge dy \implies \vec{u} = \langle u_1, u_2, u_3\rangle = \nabla \times \vec{v}$$

[1] In general, if ω is a k-form, then $d\omega$ is a $(k+1)$-form.

where $\vec{v} = \langle P, Q, R \rangle$. Using this, we see that

$$\int_B d\omega = \iint_B (\nabla \times \vec{v}) \cdot \vec{n}\, dS,$$

which recalls the familiar form of Stokes's theorem.

Recall the divergence theorem, which says that

$$\iiint_D \nabla \cdot \vec{v}\, dV = \iint_{\partial D} \vec{v} \cdot \vec{n}\, dS.$$

Here we have the 2-form

$$\omega = v_1\, dy \wedge dz + v_2\, dz \wedge dx + v_3\, dx \wedge dy$$

on ∂D. Taking the exterior derivative of ω gives the 3-form

$$\begin{aligned} d\omega = \left(\frac{\partial v_1}{\partial x}\, dx + \frac{\partial v_1}{\partial y}\, dy + \frac{\partial v_1}{\partial z}\, dz \right) \wedge dy \wedge dz. + \left(\frac{\partial v_2}{\partial x}\, dx + \frac{\partial v_2}{\partial y}\, dy + \frac{\partial v_2}{\partial z}\, dz \right) \wedge dz \wedge dx \\ + \left(\frac{\partial v_3}{\partial x}\, dx + \frac{\partial v_3}{\partial y}\, dy + \frac{\partial v_3}{\partial z}\, dz \right) \wedge dx \wedge dy \\ = \frac{\partial v_1}{\partial x} dx \wedge dy \wedge dz + \frac{\partial v_2}{\partial y} dy \wedge dz \wedge dx + \frac{\partial v_3}{\partial z} dz \wedge dx \wedge dy = \left(\frac{\partial v_1}{\partial x} + \frac{\partial v_2}{\partial y} + \frac{\partial v_3}{\partial z} \right) dx \wedge dy \wedge dz, \end{aligned}$$

which recovers the divergence of $\vec{v}$. So the divergence theorem is a special case of the generalized Stokes's theorem.

In general, for a $(k-1)$-form ω on a k-manifold B, the generalized Stokes's theorem asserts that

$$\int_B d\omega = \int_{\partial B} \omega.$$

All three of the vector calculus theorems are special cases of this.