

1 Taylor series

Lemma 1.1 (mean value theorem: integration) If $f : [a, b] \rightarrow_{\text{top}} \mathbb{R}$ and $\phi : [a, b] \rightarrow_{\text{top}} [0, \infty)$ then there is some $x : [a, b]$ s.t.

$$\int_a^b f(t)\phi(t) = f(x) \int_a^b \phi(t)dt$$

[Wik15b]

Proof. Consider the case where $\int_a^b \phi = 1$. Then it suffices to show for some $x : [a, b]$, we have $f(x) = \mathbb{E}(f; d\phi)$. By compactness, we can find some $x_{\max} : [a, b]$ maximizing f and $x_{\min} : [a, b]$ minimizing f . As $\mathbb{E}(f; d\phi) : [f(x_{\min}), f(x_{\max})]$, connectedness gives the desired x . □

Definition 1.2 (Taylor polynomial) Given $f : C^N(\mathbb{R}; \mathbb{R})$, define its N -degree Taylor polynomial centered at x_0 as

$$\text{taylor}^N_{x_0} f(x) \equiv \sum_{n=0}^N D^n f(x_0) \frac{(x - x_0)^n}{n!}$$

Theorem 1.3 (Taylor's theorem: Lagrange remainder) For $f : C^{N+1}(\mathbb{R}; \mathbb{R})$,

$$f(x) = \text{taylor}^N f(x) + \frac{1}{N!} \int_{x_0}^x D^{N+1} f(t) (x - t)^N dt$$

and for some $x^* : (x_0, x)$,

$$f(x) = \text{taylor}^N f(x) + D^{N+1} f(x^*) \frac{(x - x^*)^{N+1}}{(N + 1)!}$$

Proof. Suppose $f : C^{N+1}(\mathbb{R}; \mathbb{R})$. By the fundamental theorem of calculus,

$$f(x) = f(x_0) + \int_{x_0}^x Df(t)dt = f(x_0) + \int_{x_0}^x \underbrace{D^1 f(t)}_u \underbrace{(x - t)^0}_{dv} dt$$

Then $du = D^2 f(t)$ and $v = -(x - t)$. Integrating by parts gives

$$\begin{aligned} f(x) &= f(x_0) - Df(t)(x - t) \Big|_{t=x_0}^x + \int_{x_0}^x D^2 f(t)(x - t)dt \\ &= f(x_0) + Df(x_0)(x - x_0) + \int_{x_0}^x \underbrace{D^2 f(t)}_u \underbrace{(x - t)}_{dv} dt \\ &= f(x_0) + \dots + Df(x_0) \frac{(x - x_0)^{n-1}}{(n - 1)!} + \frac{1}{(n - 1)!} \int_{x_0}^x \underbrace{D^n f(t)}_u \underbrace{(x - t)^{n-1}}_{dv} dt \\ f(x) &= \sum_{n=0}^N D^n f(x_0) \frac{(x - x_0)^n}{n!} + \frac{1}{N!} \int_{x_0}^x D^{N+1} f(t)(x - t)^N dt \end{aligned}$$

The x^* is given by [mean value theorem: integration](#). □

Corollary 1.4 (Cauchy’s formula for repeated integration)

$$D^{-n}f(x) = \frac{1}{(n-1)!} \int_{x_0}^x f(t)(x-t)^{n-1} dt$$

[Wik15a]

Corollary 1.5 (Taylor’s theorem: no remainder) For $f : \mathbb{C}^N(\mathbb{R}; \mathbb{R})$,

$$f(x_0 + h) = \text{taylor}^N f(x_0 + h) + o(h^N)$$

Proof. By [Taylor’s theorem: Lagrange remainder](#),

$$f(x_0 + h) = \text{taylor}^{N-1} f(x_0 + h) + D^N f(x^*) \frac{(x^* - x_0)^N}{N!}$$

Suppose h is infinitesimal. Then $x^* = x_0 + h^*$, where $h^* : [0, h]$. By continuity,

$$D^N f(x_0 + h^*) \frac{(h^*)^N}{N!} = D^N f(x_0) \frac{(h^*)^N}{N!} + O(h^*) \frac{(h^*)^N}{N!}$$

So

$$D^N f(x^*) = D^N f(x_0) + O(h^{N+1}) \quad \square$$

2 Analytic functions

Definition 2.1 A function $f : \mathbb{C}^\infty(\mathbb{R}; \mathbb{R})$ is analytic in an open interval (a, b) iff $f|(a, b) = \text{taylor}^\infty f|(a, b)$. The function is analytic on \mathbb{R} iff for each $x : \mathbb{R}$, there is some open interval containing x on which f is analytic. The space of analytic functions is denoted $C^\omega(\mathbb{R}; \mathbb{R})$.

Definition 2.2 A function in $C^\omega(\mathbb{C}; \mathbb{C})$ is called entire.

Lemma 2.3 (ratio test) Let $a_n : \mathbb{C}$ be a sequence. If

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| < 1 \tag{1}$$

then $\sum_{n=0}^\infty a_n$ converges absolutely. [Wik15d]

Proof. (Adapted from [Wik15d]) For absolute convergence, it suffices to consider the case where $a_n = |a_n| : [0, \infty)$. Suppose eq. (1) holds. Let

$$r \coloneqq \lim_{n \rightarrow \infty} \frac{\frac{a_{n+1}}{a_n} + 1}{2} < 1 \tag{2}$$

For some N , for all $n \geq N$, eq. (2) gives $a_{n+1} < r a_n$. But then $a_n < r^{n-N} a_N$, so

$$\sum_{n=N}^\infty a_n \leq \sum_{n=N}^\infty r^{n-N} a_N \rightarrow 0$$

as $r < 1$. \square

Definition 2.4 (exp) Let

$$\exp(x) := \sum_{n=0}^{\infty} \frac{x^n}{n!}$$

By ratio test

$$\left| \frac{x^{n+1}}{(n+1)!} \frac{n!}{x^n} \right| = \left| \frac{x}{n+1} \right| \rightarrow 0$$

Hence $\exp : \mathbb{C} \rightarrow \mathbb{C}$ is well-defined and entire.

Lemma 2.5 (exp homeomorphism)

$$\exp(x+y) = \exp(x) \exp(y)$$

Proof.

$$\begin{aligned} \exp(x+y) &= \sum_{n=0}^{\infty} \frac{(x+y)^n}{n!} = \sum_{n=0}^{\infty} \sum_{k=1}^n \binom{n}{k} \frac{x^{n-k} y^k}{n!} \\ &= \sum_{n=0}^{\infty} \sum_{k=1}^n \frac{x^{n-k} y^k}{(n-k)! k!} \\ \exp(x) \exp(y) &= \left(\sum_{\alpha=0}^{\infty} \frac{x^{\alpha}}{\alpha!} \right) \left(\sum_{\beta=0}^{\infty} \frac{y^{\beta}}{\beta!} \right) = \sum_{\alpha=0}^{\infty} \sum_{\beta=0}^{\infty} \frac{x^{\alpha}}{\alpha!} \frac{y^{\beta}}{\beta!} \end{aligned}$$

with equivalence given by setting $\alpha = n - k$ and $\beta = k$. □

Corollary 2.6 $\exp(xn) = [\exp(x)]^n$

Lemma 2.7 $(\exp(it))^* = \exp(-it)$

Proof.

$$\begin{aligned} \exp(it) &= \sum_{n=0}^{\infty} \frac{(it)^{2n}}{(2n)!} + \frac{(it)^{2n+1}}{(2n+1)!} \\ &= \sum_{n=0}^{\infty} \frac{(-1)^n (t)^{2n}}{(2n)!} + i \frac{(-1)^n (t)^{2n+1}}{(2n+1)!} \\ \exp(-it) &= \sum_{n=0}^{\infty} \frac{(-1)^n t^{2n}}{(2n)!} - i \frac{(-1)^n t^{2n+1}}{(2n+1)!} \end{aligned}$$

□

Theorem 2.8 (Euler's theorem) The map $\exp(i-): \mathbb{R} \rightarrow \mathbb{C}$ is a universal covering map of the unit circle. In particular, $\exp(it)$ is the point on the unit circle t radians counterclockwise from 1.

Proof. As $|\exp(it)| = \exp(it) \exp(-it) = 1$, its image is contained in $S = \{z : |z| = 1\}$. Note $D \exp(it) = i \exp(it)$, so $\exp(it)$ moves clockwise. Finally, consider arc length.

$$s(t) = \int_0^t |D \exp(it)| dt = \int_0^t |i \exp(it)| dt = \int_0^t dt = t \quad \square$$

Example 2.9 (hyperbolic trig)

$$\begin{aligned} \sinh(z) &= \frac{e^z - e^{-z}}{2} \\ \cosh(z) &= \frac{e^z + e^{-z}}{2} \\ \tanh(z) &= \frac{\sinh(z)}{\cosh(z)} = \frac{e^z - e^{-z}}{e^z + e^{-z}} \end{aligned}$$

They are entire.

Example 2.10 (trig)

$$\begin{aligned} \sin(z) &= -i \sinh(iz) \\ \cos(z) &= \cosh(iz) \\ \tan(z) &= \frac{\sin z}{\cos z} \end{aligned}$$

They are entire. Note that for $x : \mathbb{R}$,

$$\begin{aligned} \sin(x) &= \Re \exp(ix) \\ \cos(x) &= \Im \exp(ix) \end{aligned}$$

Definition 2.11 (ln) Let $\ln : [0, \infty) \rightarrow_{\text{top}} \mathbb{R}$ be the inverse of \exp . The inverse function theorem guarantees its existence.

Theorem 2.12 The map $\ln(x)$ is analytic on $(0, 2)$.

Proof. By the inverse function theorem,

$$\begin{aligned} D \ln(x) &= x^{-1} \\ D^2 \ln(x) &= -x^{-2} \\ D^n \ln(x) &= (-1)^{n+1} (n-1)! x^{-n} \end{aligned}$$

So

$$\text{taylor}_1^\infty \ln(x) = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{(x-1)^n}{n}$$

But [ratio test](#) gives

$$\left|\frac{(\textcolor{teal}{x}-1)^{n+1}}{n+1}\frac{n}{(\textcolor{teal}{x}-1)^n}\right|=|\textcolor{teal}{x}-1|\frac{n}{n+1}\rightarrow|\textcolor{teal}{x}-1|$$

so $\text{taylor}_1^\infty \ln(\textcolor{teal}{x})$ converges for $\textcolor{teal}{x}:(0,2)$.

By [Taylor’s theorem: Lagrange remainder](#), for some t between 1 and $\textcolor{teal}{x}$,

$$\begin{aligned}\ln(\textcolor{teal}{x})-\text{taylor}_1^n \ln(\textcolor{teal}{x}) &= \frac{(-1)^{n+1}t^{-n-1}(\textcolor{teal}{x}-t)^{n+1}}{n+1} \\ |\ln(\textcolor{teal}{x})-\text{taylor}_1^n \ln(\textcolor{teal}{x})| &= \left|\frac{t^{-n-1}(\textcolor{teal}{x}-t)^{n+1}}{n+1}\right| \\ &\leq \left|\frac{\max(1,\textcolor{teal}{x}^{-n-1})(\textcolor{teal}{x}-1)^{n+1}}{n+1}\right|\rightarrow 0\end{aligned}$$

when $\textcolor{teal}{x}:(0,2)$. □

Corollary 2.13 The map $\sqrt{\textcolor{teal}{x}}$ is analytic on $(0,2)$.

Proof.

$$\sqrt{\textcolor{teal}{x}}=\sqrt{\exp \ln \textcolor{teal}{x}}=\exp\left(\frac{1}{2}\ln \textcolor{teal}{x}\right)$$
□

Example 2.14 ($\text{taylor}_{\sqrt{\textcolor{teal}{x}}}$)

$$\begin{aligned}D(\textcolor{teal}{x})^{1/2}&=\frac{1}{2}\textcolor{teal}{x}^{-1/2} \\ D^2(\textcolor{teal}{x})^{1/2}&=-\frac{1}{4}\textcolor{teal}{x}^{-3/2} \\ D^n(\textcolor{teal}{x})^{1/2}&=(-1)^n\frac{(2n-1)!!\textcolor{teal}{x}^{1/2-n}}{(1-2n)2^n}\end{aligned}$$

Thus

$$\text{taylor}_1^\infty \sqrt{\textcolor{teal}{x}}=\sum_{n=0}^\infty \frac{(-1)^n(2n-1)!!(\textcolor{teal}{x}-1)^n}{(1-2n)2^nn!}$$

Lemma 2.15 (double factorial)

$$(2n-1)!!=\frac{(2n)!}{2^nn!}\tag{3}$$

Proof. Base case: $n=1$. Note $1!!=1$. Likewise, note $2!/2=1$. Hence eq. [\(3\)](#) holds for $n=1$.

Suppose for the sake of induction that eq. [\(3\)](#) holds. Note $(2n+1)!!=(2n+1)(2n-1)!!$. Consider

$$\frac{(2n+2)!}{2^{n+1}(n+1)!}=\frac{(2n+2)(2n+1)(2n)!}{2(2^n)(n+1)n!}=(2n+1)n!!$$
□

Corollary 2.16

$$\text{taylor}_1^\infty \sqrt{x} = \sum_{n=1}^{\infty} \frac{(-1)^n (2n)! (x-1)^n}{(1-2n)(n!)^2 (4^n)}$$

as in [Wik15e].

3 Power series

Theorem 3.1 (radius of convergence) Let P be a power series, $a : \mathbb{C}$. If $P(a)$ converges, then for all $z : \mathbb{C}$ such that $|z| < |a|$, we have $P(z)$ converges absolutely [Nee12].

Proof. Let $P(z) = c_0 + c_1 z^1 + c_2 z^2 \dots$. By hypothesis, $P(a) = c_0 + c_1 a + c_2 a^2 + \dots$ converges. Then $c_n a^n \rightarrow 0$, so we can find some M such that $|c_n a^n| \leq M$ for all n . For $|z| < |a|$, thus $|z|/|a| < 1$,

$$\sum_{n=N}^{\infty} |c_n z^n| = \sum_{n=N}^{\infty} |c_n| |a|^n \frac{|z|^n}{|a|^n} \leq M \sum_{n=N}^{\infty} \frac{|z|^n}{|a|^n} = \frac{M \frac{|z|^N}{|a|^N}}{1 - \frac{|z|}{|a|}} \rightarrow 0$$

Hence $P(z)$ converges absolutely. [Nee12]. □

Corollary 3.2 If $P(a)$ diverges, then $P(z)$ diverges for all $z : \mathbb{C}$ such that $|z| > |a|$ [Nee12].

Theorem 3.3 (identity theorem) Let $z_n : \mathbb{C}$ be a sequence such that $z_n \rightarrow 0$. Let P and Q be power series. If $P(z_n) = Q(z_n)$, then $P = Q$. [Nee12].

Proof. Let $P(z) = a_0 + a_1 z + a_2 z^2 \dots$ and $Q(z) = b_0 + b_1 z + b_2 z^2 \dots$.

$$P(z_n) = a_0 + a_1 z_n + a_2 z_n^2 = b_0 + b_1 z_n + b_2 z_n^2 \dots = Q(z_n) \quad (4)$$

Then as $\lim P(z_n) = \lim Q(z_n)$, we have $a_0 = b_0$. Hence by eq. (4), we get

$$\begin{aligned} a_1 z_n + a_2 z_n^2 \dots &= b_1 z + b_2 z_n^2 \dots \\ a_1 + a_2 z_n^1 + a_3 z_n^2 \dots &= b_1 + b_2 z_n^1 + b_3 z_n^2 \dots \end{aligned}$$

Taking a limit gives $a_1 = b_1$. Repeating this inductively gives $P = Q$. □

4 Non-analytic smooth functions

Counter example 4.1

$$f(x) := \begin{cases} \exp(-x^{-1}), & x > 0 \\ 0, & x \leq 0 \end{cases}$$

Smoothness follows from noting

$$\begin{aligned} D^n f(0) &= \lim_{x \rightarrow 0} \frac{f(x)}{x^n} = \frac{\exp(-x^{-1})}{x^n} = \lim_{x \rightarrow 0} \frac{x^{-n}}{\exp(x^{-1})} \\ &= \lim_{x \rightarrow 0} \frac{x^{-n}}{1 + x^{-1} + x^{-2}/2 + \dots x^{-n}/n! \dots} = 0 \end{aligned}$$

with,

$$\text{taylor}_0^\infty f(x) = 0$$

hence f is not analytic at 0. [Wik15c]

References

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