Complex Analysis Lecture Notes

Hand written summary from lectures

Acknowledgment

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`http://farhi.bakir.free.fr/home/index-fr.html`

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These notes were written in real-time during the lectures, this is not the final version, yet. so they may contain :

- Incomplete or incorrect information.
- Typos, transcription mistakes, or missing content.
- Interpretations or notations that reflect my own understanding. at the moment

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Chapter 1

Power Series

Lecture 1 08:06 AM Mon, Sep 29 2025

Definition 1.0.1 (Power Series) : A power series is a formal series of the form $\sum_{n=0}^{\infty} a_n z^n$, where $a_n \in \mathbb{C}$ for all $n \in \mathbb{N}_0$.
More generally, given $z_0 \in \mathbb{C}$, a power series centered at z_0 is a formal series of the form:

$$\sum_{n=0}^{\infty} a_n (z - z_0)^n,$$

where $a_n \in \mathbb{C} \quad (\forall n \in \mathbb{N}_0)$

Remark ✎

The set of all complex power series (centered at 0) is denoted by $\mathbb{C}\,[[z]]$. More generally, given $z_0 \in \mathbb{C}$, the set of all complex power series centered at z_0 is denoted by $\mathbb{C}\,[[z - z_0]]$.

☞ Operations on Formal Power Series:

Given $z_0 \in \mathbb{C}$, we equip $\mathbb{C}\,[[z - z_0]]$. with the following operations:

① **Additions:** For all $(a_n)_{n \in \mathbb{N}_0}, (b_n)_{n \in \mathbb{N}_0} \subset \mathbb{C}$:

$$\sum_{n=0}^{\infty} a_n (z - z_0)^n + \sum_{n=0}^{\infty} b_n (z - z_0)^n = \sum_{n=0}^{\infty} (a_n + b_n)(z - z_0)^n.$$

② **Multiplication**

$$\sum_{n=0}^{\infty} a_n (z - z_0)^n \times \sum_{n=0}^{\infty} b_n (z - z_0)^n = \sum_{n=0}^{\infty} c_n (z - z_0)^n,$$

where, $c_n := \sum_{k=0}^{n} a_k b_{n-k}$ for all $n \in \mathbb{N}_0$. Also $(c_n)_{n\in\mathbb{N}}$ is called the covolution of the two sequences $(a_n)_{n\in\mathbb{N}_0}$ and $(b_n)_{n\in\mathbb{N}_0}$.

③ **Scalar Multiplication:** For all $\lambda \in \mathbb{C}$, and all $(a_n)_{n\in\mathbb{N}_0} \subset \mathbb{C}$:

$$\lambda \sum_{n=0}^{\infty} a_n (z-z_0)^n = \sum_{n=0}^{\infty} (\lambda a_n)(z-z_0)^n.$$

It's straightforward to verify that $\mathbb{C}\,[[z-z_0]]$ equipped with these operations forms a commutative algebra over $\mathbb{C}$. The Multiplicative identity is the constant power series:

$$1 = 1 + 0\cdot(z-z_0) + 0\cdot(z-z_0)^2 + \dots$$

Definition 1.0.2 (Domain of Convergence) : The domain of convergence of a power series $\sum_{n=0}^{\infty} a_n (z-z_0)^n$ is the set of all points $z \in \mathbb{C}$ for which the series converge. The structure of this domain is very specific. Its a disk (possibly with some points in its boundary) centered at z_0.

Proposition 1.0.1 (Abel's Lemma) : Let $\sum_{n=0}^{\infty} a_n (z-z_0)^n$ be a power series and let $z_1 \in \mathbb{C}\setminus\{z_0\}$. Suppose that the sequence $\{a_n(z_1-z_0)^n\}_{n\in\mathbb{N}_0}$ is bounded. Then, the power series in question converges absolutely (so converges) for every $z \in \mathbb{C}$, such that:

$$|z-z_0| < |z_1-z_0|$$

Proof. By hypothesis, $\exists M > 0$ such that $\forall n \in \mathbb{N}_0$:

$$|a_n(z_1-z_0)^n| \le M$$

Then, for all $z \in \mathbb{C}$ such that $|z-z_0| < |z_1-z_0|$ we have:

$$|a_n(z-z_0)^n| = \underbrace{|a_n(z_1-z_0)^n|}_{\le M} \cdot \underbrace{\left|\frac{z-z_0}{z_1-z_0}\right|^n}_{<1}$$

$$\le M \underbrace{\left|\frac{z-z_0}{z_1-z_0}\right|^n}_{<1}.$$

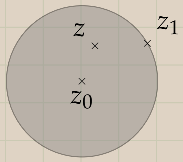
Since $\left|\frac{z-z_0}{z_1-z_0}\right| < 1$ then the geometric series

$$\sum_{n=0}^{\infty} M \left|\frac{z-z_0}{z_1-z_0}\right|^n \text{ Converges .}$$

Thus, the series $\sum_{n=0}^{\infty} |a_n(z-z_0)^n|$ also converges, that is $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ is absolutely convergent. $\square$

Corollary 1.0.2 : Let $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ be a power series which converges at some $z = z_1 \in \mathbb{C}\setminus\{z_0\}$. Then the power series in question converges absolutely (so converges), for every $z \in \mathbb{C}$ such that:

$$|z-z_0| < |z-z_1|$$



Proof. $\sum_{n=0}^{\infty} a_n(z_1-z_0)^n$ converges implies that $a_n(z-z_0)^n \to 0$ as $n \to +\infty$, which implies that the sequence $\{a_n(z_1-z_0)^n\}_{n\geq 0}$ is bounded. *Proposition 1.0.1* permits us to conclude the required result. $\square$

Theorem 1.0.3 (Radius of Convergence) : *Let $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ be a power series. Then there exists a unique $R \in [0,\infty]$, called the radius of convergence with the following properties:*

① *The power series converges absolutely for every $z \in \mathbb{C}$ satisfying $|z-z_0| < R$.*

② *The power series diverges for every $z \in \mathbb{C}$ satisfying $|z-z_0| > R$. The disk $D(z_0,R) = \{z \in \mathbb{C} : \quad |z-z_0| < R\}$ is called the disk of convergence.*

Proof. Define the set $A \subset \mathbb{R}_{\geq 0}$ of nonegative real numbers for which the sequence $\{|a_n|\, r^n\}_{n\in\mathbb{N}_0}$ is bounded.

$$A := \left\{ r \geq 0 : \quad \sup_{n\in\mathbb{N}_0} |a_n|\, r^n < \infty \right\}$$

we have $A \neq \emptyset$ because $0 \in A$. Define $R := \sup A \in [0,\infty]$, we now show that R has the stated properties.

➾① Let $z \in D(z_0,R)$. By definition of the supremum, there exists $r \in A$, (i.e., $|a_n|\, r^n$ is bounded) such that $|z-z_0| < r \leq R$. Since $|z-z_0| < r$ and $\{|a_n|\, r^n\}_{n\geq 0}$ is bounded, then by Abel's lemma, we deduce that the series $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ converges absolutely.

➾② Let $z \in \mathbb{C}$ such that $|z-z_0| > R$, suppose for contradictions that the power series converges at z. Then by the *Corollary 1.0.2*, it would converge absolutely for any ω with $|\omega-z_0| < |z-z_0|$. In particular, for any r such that:

$$R < r < |z-z_0|$$

the series would converge at points on the circle $C(z_0, r)$, implying $r \in A$. This contradicts the fact that $R = \sup A$. Therefore, the power series diverges.

➼ The Uniqueness of R:

If another $R' \in [0, \infty]$ satisfies the same properties, a point z such that $|z - z_0|$ lies between R and R' would lead to a contradiction regarding the convergence or divergence of the power series. $\square$

1.1 Formulas for Calculating the Radius of Convergence

Proposition 1.1.1 (Hadamard's Formula) : Let $\sum_{n=0}^{\infty} a_n (z - z_0)^n$ be a power series centered at $z_0 \in \mathbb{C}$. Denote by R its radius of convergence. Then:

$$\frac{1}{R} = \lim_{n \to \infty} \sup \sqrt[n]{|a_n|}$$

with the convention $\frac{1}{0} = \infty$ and $\frac{1}{\infty} = 0$

Proof. Let $L := \lim_{n \to \infty} \sup |a_n|^{\frac{1}{n}} \in [0, \infty]$. We must show that $R = \frac{1}{L}$. Let $z \in \mathbb{C} \setminus \{z_0\}$, we distinguish three cases:

➼① If $L = 0$. In this case, we have:

$$0 \leq \lim_{n \to \infty} \inf |a_n|^{\frac{1}{n}} \leq \lim_{n \to \infty} \sup |a_n|^{\frac{1}{n}} = 0$$

Thus, $\lim_{n \to \infty} \inf |a_n|^{\frac{1}{n}} = \lim_{n \to \infty} \sup |a_n|^{\frac{1}{n}} = 0$. This implies that $\lim_{n \to \infty} |a_n|^{\frac{1}{n}}$ exists and equals to 0, so for all n sufficiently large, we have:

$$|a_n|^{\frac{1}{n}} < \frac{1}{2|z - z_0|};$$

That is,

$$|a_n (z - z_0)^n| < \frac{1}{2^n}.$$

Since the geometric series $\sum_{n=1}^{\infty} \frac{1}{2^n}$ converges then the series $\sum_{n=0}^{\infty} |a_n (z - z_0)^n|$ converges $\forall z \in \mathbb{C}$, thus $R = +\infty = \frac{1}{L}$

➼ ② If $L = +\infty$, we have $L = \lim_{n \to \infty} \sup |a_n|^{\frac{1}{n}} = +\infty$ is equivallent to the fact that the sequence $\left\{ |a_n|^{\frac{1}{n}} \right\}_{n \in \mathbb{N}}$ is bounded. Therefore, the sequence:

$$|a_n (z - z_0)^n|^{\frac{1}{n}} = |a_n|^{\frac{1}{n}} |z - z_0|$$

is also unbounded. This implies that $|a_n(z-z_0)^n|$ is unbounded, thus $|a_n(z-z_0)^n|$ does not converge to 0 as $n \to \infty$. Hence $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ diverges. Hence $R = 0$.

➜ ③ If$L \in (0, \infty)$. Let $z \in \mathbb{C}$. We consider two subcases:

- ❶ If $|z-z_0| < \frac{1}{L}$. Choose r such that $|z-z_0| < r < \frac{1}{L}$, thus $L < \frac{1}{r}$. By defintion of a $\lim_{n\to\infty} \sup$, for all n sufficiently large we have:

$$|a_n|^{\frac{1}{n}} < \frac{1}{r},$$

which implies that:

$$|a_n(z-z_0)^n| < \underbrace{\left(\frac{|z-z_0|}{r}\right)^n}_{<1}.$$

Since $\left|\frac{z-z_0}{r}\right| < 1$, the geometric series $\sum_{n=0}^{\infty} \left|\frac{z-z_0}{r}\right|^n$ converges. By comparison, the power series $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ converges absolutely.

- ❷ If $(|z-z_0| > \frac{1}{L})$. In this case, we have:

$$\begin{aligned}\lim_{n\to\infty} \sup |a_n(z-z_0)^n|^{\frac{1}{n}} &= \lim_{n\to\infty} \sup \left(|a_n|^{\frac{1}{n}} |z-z_0|\right) \\ &= L\,|z-z_0| > 1\end{aligned}$$

Thus, $\{a_n(z-z_0)^n\}_{n\in\mathbb{N}}$ is unbounded, hence $|a_n(z-z_0)^n|$ does not converge to zero as $n \to \infty$, implying that $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ diverges. Therefore:

$$R = \frac{1}{L}.$$

□

Lecture 2

08:00 AM Mon, Oct 06 2025

Proposition 1.1.2 (Ratio Test Formula) : Let $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ be a power series. Suppose that the limit

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

exists (i.e., $\in [0, \infty]$). Then the radius of convergence R of the power series in question is $R = \alpha$.

Proof. We use the d'Allembert rule for the series

$$\sum_{n=0}^{\infty} a_n(z-z_0)^n \qquad (z \in \mathbb{C} \setminus \{z_0\}).$$

Let $z \in \mathbb{C} \setminus \{z_0\}$. we have:

$$\begin{aligned}
\lim_{n\to\infty} \left| \frac{a_{n+1}(z-z_0)^{n+1}}{a_n(z-z_0)^n} \right| &= \lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| \cdot |z-z_0| \\
&= |z-z_0| \cdot \lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| \\
&= \frac{|z-z_0|}{\alpha}
\end{aligned}$$

By the d'Allembert rule, we have:

- The series $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ converges if

$$\frac{|z-z_0|}{\alpha} < 1 \quad \text{i.e.} \quad |z-z_0| < \alpha.$$

- The series $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ diverges if

$$\frac{|z-z_0|}{\alpha} > 1 \quad \text{i.e.} \quad |z-z_0| > \alpha.$$

Hence $R = \alpha$.

□

Example: *Determine the radius of convergence of the power series $\sum_{n=0}^{\infty} \frac{z_n}{n!}$ where $z_0 = 0$.*

1^{st} METHOD: (BY HADAMARD FORMULA)

We must compute $\lim_{n\to\infty} \sup \left(\frac{1}{n!}\right)^{\frac{1}{n}}$. By the stirling formula, we have that:

$$n! \sim_{+\infty} n^n e^{-n} \sqrt{2\pi n}.$$

Thus we get:

$$(n!)^{\frac{1}{n}} \sim_{+\infty} n e^{-1} (2\pi n)^{\frac{1}{2n}}.$$

Thus

$$\left(\frac{1}{n!}\right)^{\frac{1}{n}} \sim_{+\infty} \frac{e}{n} (2\pi n)^{-\frac{1}{2n}} \to 0 \text{ as } n \to +\infty .$$

Thus $R = \frac{1}{0} = +\infty$.

This means that the power series $\sum_{n=0}^{\infty} \frac{z^n}{n!}$ converges for all $z \in \mathbb{C}$.

2 nd METHOD:

We use Proposition 2 . we have:

$$\begin{aligned}\lim_{n\to\infty}\left|\frac{\frac{1}{n!}}{\frac{1}{(n+1)!}}\right| &= \lim_{n\to\infty}\frac{(n+1)!}{n!}\\ &= \lim_{n\to\infty}(n+1) = +\infty.\end{aligned}$$

Thus $R = +\infty$

1.2 Analytic Functions

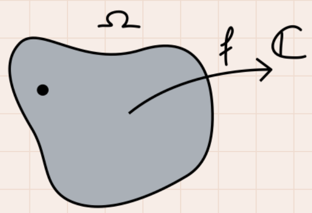
Definition 1.2.1 : Let Ω be a non empty open subset of $\mathbb{C}$ and let $z_0 \in \Omega$.

Let $f : \Omega \longrightarrow \mathbb{C}$ be a map. then:

1. f is said to be analytic at z_0 if there exists $r > 0$ and a complex sequence $(a_n)_{n\in\mathbb{N}_0}$ such that $D(z_0, r) \subset \Omega$ and:

$$f(z) = \sum_{n=0}^{\infty} a_n (z - z_0)^n \quad (\forall z \in D(z_0, r)).$$

2. f is said to be analytic on Ω if its analytic at every point of Ω.



Example:

1. *Every complex polynomial is analytic on* $\mathbb{C}$. *Indeed, let* $P \in \mathbb{C}[\mathbb{Z}]$, *and* $z_0 \in \mathbb{C}$. *since*

$P(z+z_0) \in \mathbb{C}[\mathbb{Z}]$, we can write:

$$P(z+z_0) = \sum_{n=0}^{d} a_n z^n \quad (d \in \mathbb{N}_0).$$

Substituting z by $(z-z_0)$, we get:

$$P(z) = \sum_{n=0}^{d} a_n (z-z_0)^n,$$

which is a power series centered at z_0 with infinite randius of convergence. Thus, P is analytic at z_0. Since z_0 was arbitrary, P is analytic on $\mathbb{C}$.

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2. *The function $z \longrightarrow \frac{1}{z}$ is analytic on $\mathbb{C}^* = \mathbb{C}\setminus\{0\}$. Indeed, let $z_0 \in \mathbb{C}^*$ arbitrary.*

   For $z \in D(z_0, |z_0|)$, we have:

$$\left|\frac{z-z_0}{z_0}\right| < 1.$$

   We can write

$$\begin{aligned} \frac{1}{z} &= \frac{1}{z_0 + (z-z_0)} \\ &= \frac{1}{z_0} \cdot \frac{1}{1 + \frac{z-z_0}{z_0}} \\ &= \frac{1}{z_0} \cdot \sum_{n=0}^{\infty} (-1)^n \left(\frac{z-z_0}{z_0}\right)^n \\ &= \sum_{n=0}^{\infty} \frac{(-1)^n}{z_0^{n+1}} (z-z_0)^n, \end{aligned}$$

   which is a power series centered at z_0, valid on $D(z_0, |z_0|)$. Hence $z \longrightarrow \frac{1}{z}$ is analytic at z_0. Since $z_0 \in \mathbb{C}^*$ was arbitrary, then $z \longrightarrow \frac{1}{z}$ is analytic on $\mathbb{C}^*$.

1.2.1 Properties of Analytic Functions

Proposition 1.2.1 : Let Ω be a non empty open subset of $\mathbb{C}$ and let $z_0 \in \Omega$. If $f, g : \Omega \longrightarrow \mathbb{C}$ are analytic at z_0, then the same is for $(f+g)$ and $(f \cdot g)$. Moreover, if f and g are represented by power series with radii of convergence R_f and R_g respectively then $(f+g)$ and $(f \cdot g)$ are represented by power series with radii of convergence $\geq \min(R_f, R_g)$.

Proof. Exercise. □

Corollary 1.2.2 : Let Ω be a non empty open subset of $\mathbb{C}$ and let $f, g : \Omega \longrightarrow \mathbb{C}$. If f and g are both analytic on Ω, then the same is for $(f+g)$ and $(f \cdot g)$.

Proposition 1.2.3 (Analyticity $\implies$ Continuity) : Let Ω be a non empty open subset of $\mathbb{C}$ and let $z_0 \in \Omega$. Let also $f : \Omega \longrightarrow \mathbb{C}$ be a map. If f is analytic at z_0 then f is continuous at z_0

Proof. Suppose that f is analytic at z_0 then there exists $R > 0$ and a complex sequence $(a_n)_{n\in\mathbb{N}_0}$ such that $D(z_0, R) \subset \Omega$ and:

$$f(z) = \sum_{n=0}^{\infty} a_n (z - z_0)^n \quad (\forall z \in D(z_0, R))$$

In particular, $f(z_0) = a_0$. Thus for all $z \in D(z_0, R)$ we have:

$$\begin{aligned} f(z) - f(z_0) &= \sum_{n=1}^{\infty} a_n (z - z_0)^n \\ &= (z - z_0) \sum_{n=1}^{\infty} a_n (z - z_0)^{n-1} \\ &= (z - z_0) \sum_{n=0}^{\infty} a_{n+1} (z - z_0)^n \qquad (1) \end{aligned}$$

By the Hadamard formula, we see that the power series $\sum_{n=0}^{\infty} a_{n+1}(z - z_0)^n$ has the same radius of convergence as the original power series $\sum_{n=0}^{\infty} a_n (z - z_0)^n$. Consequently, the power series $\sum_{n=0}^{\infty} a_{n+1}(z - z_0)^n$ converges absolutely for $|z - z_0| < R$. Let $r \in \mathbb{R}$ such that $0 < r < R$. Then for all $z \in D(z_0, r)$, we have from (1) the estimate:

$$\begin{aligned} |f(z) - f(z_0)| &= |z - z_0| \cdot \left| \sum_{n=0}^{\infty} a_{n+1}(z - z_0)^n \right| \\ &\leq |z - z_0| \sum_{n=0}^{\infty} |a_{n+1}| \, |z - z_0|^n \\ &\leq |z - z_0| \underbrace{\sum_{n=0}^{\infty} |a_{n+1}| \cdot r^n}_{<+\infty \text{ since } r<R} . \end{aligned}$$

Taking the limit as $z \to z_0$, we conclude that $\lim_{z\to z_0} f(z) = f(z_0)$, so f is continuous at z_0. □

Corollary 1.2.4 (Immediate) : Let Ω be a non empty open subset of $\mathbb{C}$ and $f : \Omega \longrightarrow \mathbb{C}$. If f is analytic on Ω, then f is continuous on Ω.

Proposition 1.2.5 (Composition of Analytic functions) : Let Ω_1 and Ω_2 be two nonempty open subsets of $\mathbb{C}$ and let $f : \Omega_1 \longrightarrow \Omega_2$ and $g : \Omega_2 \longrightarrow \mathbb{C}$ be two maps. Let also $z_0 \in \Omega_1$. If f is analytic at z_0 and g is analytic at $f(z_0)$, then $(g \circ f)$ is analytic at z_0.

Proof. Exercise □

Corollary 1.2.6 (Immediate) : Let Ω_1 and Ω_2 be two nonempty open subsets of $\mathbb{C}$ and let $f : \Omega_1 \longrightarrow \Omega_2$ and $g : \Omega_2 \longrightarrow \mathbb{C}$ be two maps. If f is analytic on Ω_1 and g is analytic on Ω_2 then $(g \circ f)$ is analytic on Ω_1.

Proposition 1.2.7 (Quotient of Analytic Functions) : Let Ω be a nonempty open subsets of $\mathbb{C}$ and let $z_0 \in \Omega$. Let also $f, g : \Omega \longrightarrow \mathbb{C}$ be two functions which are both analytic at z_0 and such that $g(z_0) \neq 0$. Then the function $\frac{f}{g}$ is analytic at z_0.

Proof. Since $g(z_0) \neq 0$ then the function $h : w \longrightarrow \frac{1}{w}$ is analytic at $g(z_0)$ (as seen in previous examples). Therefore, by *Proposition* 1.2.5, the function $\frac{1}{g} = h \circ g$ is anayltic at z_0.
It then follows from *Proposition* 1.2.1 that the product $f \cdot \left(\frac{1}{g}\right)$ is analytic at z_0. □

Corollary 1.2.8 (Immediate) : Let Ω be a non empty open subset of $\mathbb{C}$ and let $f, g : \Omega \longrightarrow \mathbb{C}$ be two analytic functions on Ω such that $g(z) \neq 0$ for every $z \in \Omega$. Then the function $\frac{f}{g}$ is analytic on Ω .

Example: *Every rational function is analytic on its domain of definition. This is because a rational function is a quotient of two polynomials, and polynomials are analytic on* $\mathbb{C}$.

- -

1.3 Power series define Analytic functions

Theorem 1.3.1 : *A power series with a positive radius of converges defines an analytic function on its disk of convergence.*

Proof. Let $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ be a power series ($z_0 \in \mathbb{C}$, $(a_n)_{n\in\mathbb{N})} \subset \mathbb{C}$) with radius of convergence $R > 0$. Define the function f on the disk $D(z_0, R)$ by:

$$f(z) = \sum_{n=0}^{\infty} a_n(z-z_0)^n.$$

We must show that f is analytic on $D(z_0, R)$. Let $z_1 \in D(z_0, R)$ arbitrary. We will show that f is analytic at z_1. For $z \in D(z_1, R - |z_1 - z_0|)$, we have

$$|z - z_0| \overset{T.I}{\leq} \underbrace{|z - z_1|}_{<R-|z_1-z_0|} + |z_1 - z_0| < R$$

Thus $D(z_1, R - |z_1 - z_0|) \subset D(z_0, R)$, so the power series $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ converges absolutely. so:

$$\begin{aligned}
f(z) &= \sum_{n=0}^{\infty} a_n(z-z_0)^n \\
&= \sum_{n=0}^{\infty} a_n((z-z_1)+(z_1-z_0))^n \\
&= \sum_{n=0}^{\infty} a_n \sum_{k=0}^{n} \binom{n}{k} (z-z_1)^k (z_1-z_0)^{n-k} \\
&= \sum_{k=0}^{\infty} \left(\sum_{n=k}^{\infty} a_k \binom{n}{k} (z_1-z_0)^{n-k} \right) (z-z_1)^k
\end{aligned}$$

The interchange of summation is justified by the absolute convergence of the double series for $z \in D(z_1, R - |z_1 - z_0|)$. This express $f(z)$ as a power series in $(z - z_1)$ in the disk $D(z_1, R - |z_1 - z_0|)$, proving that f is analytic at z_1. Since z_1 was arbitrary in $D(z_0, R)$, then f is analytic on $D(z_0, R)$. □

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Example: *The power series $\sum_{n=0}^{\infty} \frac{z^n}{n!}$ has radius of convergence $R = +\infty$. Therefore (by the previous Theorem), it defines an analytic function on the whole complex plane $\mathbb{C}$.*

Definition 1.3.1 : The analytic function on $\mathbb{C}$ defined by:

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

is called the exponential function.

Definition 1.3.2 (Entire function) : A complex function $f : \mathbb{C} \longrightarrow \mathbb{C}$ which is analytic on the whole complex plane $\mathbb{C}$ is called an entire function.

Example:

① *Every complex polynomial is an entire function.*

② *The exponential function* $\exp(z)$ *is an entire function.*

1.3.1 Properties of the exponential function

Proposition 1.3.2 : The exponential function defines the following properties:

① $\forall z_1, z_2 \in \mathbb{C}$, we have:

$$e^{z_1+z_2} = e^{z_1} \cdot e^{z_2} \text{ and } e^{z_1-z_2} = \frac{e^{z_1}}{e^{z_2}}.$$

② for all $z \in \mathbb{C}$, we have $e^z \neq 0$.

③ (EULER'S FORMULA): $\forall \theta \in \mathbb{R}$, we have:

$$e^{i\theta} = \cos\theta + i\sin\theta.$$

④ $\forall z \in \mathbb{C}$, we have:

$$e^z = 1 \iff z \in 2\pi i\mathbb{Z}.$$

More generally, for all $z, z' \in \mathbb{C}$, we have:

$$e^z = e^{z'} \iff z - z' \in 2\pi\mathbb{Z}.$$

So, the exponential function is periodic with period $2\pi i$.

Proof.

① $\forall z_1, z_2 \in \mathbb{C}$, we have

$$\begin{aligned} e^{z_1} \cdot e^{z_2} &= \sum_{k=0}^{+\infty} \frac{z_1^k}{k!} \cdot \sum_{\ell=0}^{+\infty} \frac{z_2^\ell}{\ell!} \\ &= \sum_{k,\ell \in \mathbb{N}_0} \frac{z_1^k z_2^\ell}{k!\ell!} \\ &= \sum_{n=0}^{+\infty} \left(\sum_{k,\ell \in \mathbb{N}_0, k+\ell=n} \frac{z_1^k z_2^\ell}{k!\ell!} \right) \\ &= \sum_{n=0}^{+\infty} \left(\sum_{k=0}^{n} \frac{z_1^k z_2^{n-k}}{k!(n-k)!} \right) \\ &= \sum_{n=0}^{+\infty} \frac{1}{n!} \underbrace{\left(\sum_{k=0}^{n} \frac{n!}{k!(n-k)!} z_1^k z_2^{n-k} \right)}_{=\sum_{k=0}^{n} \binom{n}{k} z_1^k z_2^{n-k} = (z_1+z_2)^n} \\ &= \sum_{n=0}^{+\infty} \frac{1}{n!} (z_1+z_2)^n = e^{z_1+z_2}, \end{aligned}$$

next, we have:

$$e^{z_1 - z_2} \cdot e^{z_2} \overset{\text{by the first formula}}{=} e^{z_1 - z_2 + z_2} = e^{z_1}.$$

Hence $e^{z_1 - z_2} = \frac{e^{z_1}}{e^{z_2}}$, as required.

② For all $z \in \mathbb{C}$, we have:

$$e^z \cdot e^{-z} \overset{(1)}{=} e^{z-z} = e^0 = 1.$$

Thus $e^z \neq 0$.

③ (Euler's Formula).

For all $\theta \in \mathbb{R}$, we have:

$$\begin{aligned} e^{i\theta} &= \sum_{n=0}^{+\infty} \frac{(i\theta)^n}{n!} \\ &= \sum_{n=0}^{+\infty} i^n \frac{\theta^n}{n!} \\ &= \sum_{n \in \mathbb{N}_0,\, n \text{ is even}} i^n \frac{\theta^n}{n!} + \sum_{n \in \mathbb{N}_0,\, n \text{ is odd}} i^n \frac{\theta^n}{n!} \\ &= \sum_{k=0}^{+\infty} i^{2k} \frac{\theta^{2k}}{(2k)!} + \sum_{k=0}^{+\infty} i^{2k+1} \frac{\theta^{2k+1}}{(2k+1)!} \\ &= \underbrace{\sum_{k=0}^{+\infty} (-1)^k \frac{\theta^{2k}}{(2k)!}}_{\cos\theta} + i \underbrace{\sum_{k=0}^{+\infty} (-1)^k \frac{\theta^{2k+1}}{(2k+1)!}}_{\sin\theta} \\ &= \cos\theta + i \sin\theta, \end{aligned}$$

as required.

➭ ④ Let $z \in \mathbb{C}$ and write

$$z = x + iy \qquad (x, y \in \mathbb{R}).$$

we have

$$\begin{aligned} e^z &= e^{x+iy} \\ &\overset{(1)}{=} e^x \cdot e^{iy} \\ &\overset{(3)}{=} e^x(\cos y + i \sin y) \\ &= e^x \cos y + ie^x \sin y. \end{aligned}$$

Thus

$$\begin{aligned} e^z = 1 \iff & \begin{cases} e^x \cos y = 1 \\ e^x \sin y = 0 \end{cases} \iff \begin{cases} \cos y = e^{-x} > 0 \\ \sin y = 0 \end{cases} \\ \iff & \begin{cases} \exists k \in \mathbb{Z}: \quad y = 2\pi k \\ e^{-x} = \cos 2\pi k = 1 \end{cases} \iff \begin{cases} \exists k \in \mathbb{Z}: \quad y = 2\pi k \\ x = 0 \end{cases} \\ \iff & z = 2\pi k i \qquad (k \in \mathbb{Z}) \\ \iff & z \in 2\pi \mathbb{Z}, \end{aligned}$$

as required. □

1.3.2 Trigonometric and hyperbolic functions

Definition 1.3.3 (Complex Trigonometric functions) : We define the trigonometric functions cosine and sine by:

$$\begin{aligned} \cos z &:= \sum_{n=0}^{+\infty} (-1)^n \frac{z^{2n}}{(2n)!}, \\ \sin z &:= \sum_{n=0}^{+\infty} (-1)^n \frac{z^{2n+1}}{(2n+1)!} \qquad (\forall z \in \mathbb{C}). \end{aligned}$$

Clearly, these functions extend the real functions cos and sin. The power series defining cos and sin have infinite radius of convergence, thus (By a previous theorem) cos and sin are analytic on $\mathbb{C}$; that is, cos and sin are entire functions.

Remark ✎

We easily verify the extended Euler's formula:

$$e^{iz} = \cos z + i \sin z \qquad (\forall z \in \mathbb{C}).$$

From this formula, we derive:

$$\begin{aligned} \cos z &= \frac{e^{iz} + e^{-iz}}{2}, \\ \sin z &= \frac{e^{iz} - e^{-iz}}{2i} \qquad (\forall z \in \mathbb{C}). \end{aligned}$$

These functions are not bounded in $\mathbb{C}$, when you replace $x \leftarrow ix$, you get $\cos ix = \cosh x$.

Exercise

Using property ④ of *Proposition 1.3.2* and Euler's formula, show the following properties:

① The functions cos and sin are both 2π-periodic.

② The set of zeros of $z \mapsto \cos z$ is $(\frac{\pi}{2} + \pi\mathbb{Z})$, while the set of zeros of $z \mapsto \sin z$ is $\pi\mathbb{Z}$.

③ For all $z \in \mathbb{C}$, we have

$$\cos^2 z + \sin^2 z = 1.$$

☞ FOR EXAMPLE, FOR ③: By the Euler formula, we have for all $z \in \mathbb{C}$:

$$\begin{aligned} \cos^2 z + \sin^2 z &= \left(\frac{e^{iz} + e^{-iz}}{2}\right)^2 + \left(\frac{e^{iz} - e^{-iz}}{2i}\right)^2 \\ &= \frac{4}{4} = 1 \end{aligned}$$

Definition 1.3.4 (Complex hyperbolic functions) : We define the hyperbolic functions cosh and sinh by:

$$\begin{aligned} \cosh z &:= \sum_{n=0}^{+\infty} \frac{z^{2n}}{(2n)!} = \frac{e^z + e^{-z}}{2} = \cos(iz), \\ \sinh z &:= \sum_{n=0}^{+\infty} \frac{z^{2n+1}}{(2n+1)!} = \frac{e^z - e^{-z}}{2} = -i \sin(iz) \qquad (\forall z \in \mathbb{C}). \end{aligned}$$

Clearly, these definitions extend the real functions cosh and sinh. Like the trigonometric functions cos and sin, the hyperbolic functions cosh and sinh are also entire functions.

Exercise

Using the expressions of cosh and sinh in terms of cos and sin, verify the following properties:

① The functions cosh and sinh are both $2\pi-$periodic.

② The set of zeros of cosh is $(\frac{\pi}{2}i + \pi i\mathbb{Z})$, while the set of zeros of sinh is $\pi i\mathbb{Z}$.

③ For all $z \in \mathbb{C}$, we have

$$\cosh^2 z - \sinh^2 z = 1.$$

Definition 1.3.5 (Further trigonometric and hyperbolic functions) : We define the following functions:

$$\begin{aligned}
\tan z &:= \frac{\sin z}{\cos z} && \left(\forall z \in \mathbb{C}\backslash \left(\frac{\pi}{2} + \pi\mathbb{Z}\right)\right),\\
\cot z &:= \frac{\cos z}{\sin z} && (\forall z \in \mathbb{C}\backslash \pi\mathbb{Z}),\\
\tanh z &:= \frac{\sinh z}{\cosh z} && \left(\forall z \in \mathbb{C}\backslash \left(\frac{\pi}{2}i + \pi i\mathbb{Z}\right)\right),\\
\coth z &:= \frac{\cosh z}{\sinh z} && (\forall z \in \mathbb{C}\backslash \pi i\mathbb{Z}).
\end{aligned}$$

This clearly extends the well-known real functions tan, cot, tanh, and coth. Note that each of these four functions is analytic in its domain of definition (according to the previous results on analytic functions).

1.4 Holomorph functions

Definition 1.4.1 : Let Ω be a nonempty open subset of $\mathbb{C}$ and z_0 be a point in Ω. Let also $f : \Omega \longrightarrow \mathbb{C}$ be a map.

- We say that f is holomorphic at z_0 if the limit

$$\lim_{z \to z_0} \frac{f(z) - f(z_0)}{z - z_0}$$

exists and belong to $\mathbb{C}$. In this case, the limit is called the derivative of f at the point z_0 and denoted by $f'(z_0)$.

- We say that f is holomorphic on Ω if it is holomorphic at every point in Ω.

In this case, the function

$$\begin{array}{rccc} f' : & \Omega & \longrightarrow & \mathbb{C} \\ & z & \longmapsto & f'(z) \end{array}$$

is called the derivative of f.

Proposition 1.4.1 (Holomorphy of power series) : Let $z_0 \in \mathbb{C}$, $(a_n)_{n\in\mathbb{N}_0} \subset \mathbb{C}$, and S be the power series

$$S(z) = \sum_{n=0}^{+\infty} a_n (z - z_0)^n.$$

Suppose that S has a positive radius of convergence R. Then S is holomorphic on $D(z_0, R)$ and we have for all $z \in D(z_0, R)$:

$$\begin{aligned} S'(z) &= \sum_{n=0}^{+\infty} n a_n (z - z_0)^{n-1} \\ &= \sum_{n=0}^{+\infty} (n+1) a_{n+1} (z - z_0)^n. \end{aligned}$$

Proof. For simplicity, suppose without loss of generality that $z_0 = 0$. First, remark that by using the Hadamard formula, the power series

$$\sum_{n=1}^{+\infty} n a_n z^{n-1} = \sum_{n=0}^{+\infty} (n+1) a_{n+1} z^n$$

has the same radius of convergence R as S. It follows that $\sum_{n=1}^{+\infty} n a_n z^{n-1}$ is absolutely convergent on $D(0, R)$; That is, for all $0 < r < R$, the series $\sum_{n=1}^{+\infty} n\, |a_n|\, z^{n-1}$ converges. Now, let $z_1 \in D(0, R)$ be arbitrary and show that S is holomorphic at z_1. Choose $r \in \mathbb{R}$ such that $|z_1| < r < R$. For all $z \in D(0, r) \setminus \{z_1\}$, we have

$$\begin{aligned} \frac{S(z) - S(z_1)}{z - z_1} &= \frac{\sum_{n=0}^{+\infty} a_n z^n - \sum_{n=0}^{+\infty} a_n z_1^n}{z - z_1} \\ &= \sum_{n=0}^{+\infty} a_n \frac{z^n - z_1^n}{z - z_1} \\ &= \sum_{n=1}^{+\infty} a_n \sum_{k=0}^{n-1} z^k z_1^{n-1-k}. \end{aligned}$$

□