

Math remark

foundation for analysis and probability

X

ElegantL^AT_EX Program

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1 Genenralisation of several inequalities

1.1 Jense,Hölder,Minkeoski's inequalities

The description of the Jense inequality depends on the properties of the convex function, it is a strong inequalities which can be applied in many places. We should pay a little attention to the outline of the section:

$$\text{Jense} \Rightarrow \text{Hölder} \Rightarrow \text{Minkeoski}$$

Theorem 1.1 (Jense)

Suppose $\varphi : I \rightarrow \mathbb{R}$ is a convex function defined on an interval, (X, \mathcal{E}, μ) is a probability space and $f \in L^1(X)$ with $\text{im} f \subset I$, then $\int_X f d\mu \in I$ and $\varphi \circ f$ is integrable such that

$$\varphi\left(\int_X f d\mu\right) \leq \int_X \varphi \circ f d\mu$$

The equality holds iff f is constant almost everywhere.

Proof.



Remark There are many other forms of the Jense's inequality, we take some examples.

- **Finite forms:** the motivation of the inequality comes from the definition of the convex function, i.e. the real-valued function satisfies

$$f(tx + (1 - t)y) \leq tf(x) + (1 - t)f(y)$$

for any defined x, y and $t \in [0, 1]$, here a question about the distribution of the weights appears, which is the core of the convex function. we can generalize the inequalities by applying the weights to the n different points in interval such that $\sum_i w_i = 1$, then we can conclude the inequality:

$$f(\sum_i w_i x_i) \leq \sum_i w_i f(x_i)$$

notice that the defined domain usually is a convex set, which ensures the effectivity of $f(\sum_i w_i x_i)$.

- **Expectation:** By a simple change of the notation, the Jense inequality in a probability space can be written as the form:

$$\varphi(E[X]) \leq E[\varphi(X)]$$

Applying a classic convex function $t \mapsto t^2$ we can get the important inequality in probability:

$$E^2[X] \leq E[X^2]$$

- **Concave:** some function like $t \mapsto \ln t$ is a concave function, the Jense's inequality can be just changed the order of the inequality. The reason is simple, if f is a concave function, then $-f$ will be a convex function.

The classic proof of the Hölder's inequality covers the inequality of Young:

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}$$

for any $a, b \geq 0$ and $p, q > 1$ such that $1/p + 1/q = 1$. The complete proof can be found in **[Rudin 1 Ex 6.10]**. I don't choose the proof here for a comparison of strength of the different inequality. Here the proof is elegant and given by Mon.Mardare in TD, and a similar proof via Jense can be found in **[SU TD1 EX15-16]**.

Theorem 1.2 (Hölder)

Suppose that $p, q > 1$ and $1/p + 1/q = 1$, for any two mesurable functions $f, g : (X, \mathcal{E}, \mu) \rightarrow \mathbb{C}$, we have

$$\int_X |fg| d\mu \leq \left(\int_X |f|^p d\mu \right)^{1/p} \left(\int_X |g|^q d\mu \right)^{1/q}$$

the equality holds iff $|f| = c|g|$ almost everywhere (u - p , p) for some constant c .

Proof. Let $u = \frac{|f|}{\|f\|_p}$ and $v = \frac{|g|}{\|g\|_q}$, then notice that $\|u\|_p = \|v\|_q = 1$. We know $t \mapsto \ln t$ is a concave function on $(0, +\infty)$, so we can estimate by Jense's inequality

$$\begin{aligned} \ln(uv) &= \ln(u + v) = \frac{1}{p}\ln u^p + \frac{1}{q}\ln v^q \\ &\leq \ln\left(\frac{1}{p}u^p + \frac{1}{q}v^q\right) \end{aligned}$$

by the monotone of the function, we have $uv \leq \frac{1}{p}u^p + \frac{1}{q}v^q$, hence we can conclude

$$\begin{aligned} \frac{\int_X |fg| d\mu}{(\int_X |f|^p d\mu)^{1/p} (\int_X |g|^q d\mu)^{1/q}} &= \int_X uv d\mu \\ &\leq \frac{1}{p} \int_X u^p d\mu + \frac{1}{q} \int_X v^q d\mu \\ &= \frac{1}{p} \|u\|_p^p + \frac{1}{q} \|v\|_q^q = 1 \end{aligned}$$

finally, we discuss the equality. By Jense, we know the equality holds iff $u = v$. Notice that if $u = 0$ or $v = 0$ almost everywhere, then the inequality can be reduced to $0 \leq 0$, it holds, otherwise we can get that $|f| = \frac{\|f\|_p}{\|g\|_q} |g|$, so we finish the proof. ■

Corollary (Cauchy-Schwartz)

For any two square integrable function $f, g \in L^2_{\mathbb{C}}(\mathbb{R}^n)$, we have

$$\left| \int_{\mathbb{R}^n} f \bar{g} dl \right|^2 \leq \int_{\mathbb{R}^n} |f|^2 dl \cdot \int_{\mathbb{R}^n} |g|^2 dl$$

The equality holds iff $|f| = c|g|$ almost everywhere (u.p.p) for some constant c .

Proof. Although it is the special case of Hölder when $p = q = 2$, but usually in a Hilbert space we have the beautiful form as following

$$| \langle u, v \rangle | \leq \|u\| \|v\|$$

the inequality has a good geometric intuition, and the proof of it is very beautiful and elementary. Notice $\langle u, v \rangle \in \mathbb{C}$, so there exists $z \in \mathbb{C}$ such that $|z| = 1$ and $z \langle u, v \rangle = |\langle u, v \rangle|$, and we let $p(t) = \langle tzu + v, tzu + v \rangle$ defined on \mathbb{R} , then

$$\begin{aligned} p(t) &= t^2 z \bar{z} \langle u, u \rangle + tz \langle u, v \rangle + t \bar{z} \langle v, u \rangle + \langle v, v \rangle \\ &= t^2 z \bar{z} \langle u, u \rangle + tz \langle u, v \rangle + \overline{tz \langle u, v \rangle} + \langle v, v \rangle \\ &= t^2 \|u\|^2 + 2|\langle u, v \rangle| t + \|v\|^2 \end{aligned}$$

so $p(t)$ can be arranged to be a quadratic polynomial with respect to real value t , and $p(t) = \|tzu + v\|^2 \geq 0$, so we have sufficient and necessary condition that

$$\Delta = 4|\langle u, v \rangle|^2 - 4\|u\|^2 \|v\|^2 \geq 0$$

which is the inequality we hope to get, and $\Delta = 0$ happens iff the polynomial satisfies $p(t) = (t\|u\| + \|v\|)^2 = 0$. ■

Theorem 1.3 (Minkowski)

For any $p \geq 1$, suppose that $f, g : (X, \mathcal{E}, \mu) \rightarrow \mathbb{C}$ are two measurable functions, then we have

$$\left(\int_X |f + g|^p d\mu\right)^{1/p} \leq \left(\int_X |f|^p d\mu\right)^{1/p} + \left(\int_X |g|^p d\mu\right)^{1/p}$$

The equality holds iff $|f| = c|g|$ almost everywhere (u.p.p) for some constant c .

Proof. If ■

Review some basic inequalities (discrete)...

1.2 Markov, Tchebychev, Cantelli's inequalities

This section covers some basic inequalities in properties, They are always very useful when estimation. And in this section ,we always use (Ω, \mathcal{T}, P) to denote a probability space

Theorem 1.4 (Markov)

Suppose that $Y : \Omega \rightarrow \mathbb{R}^+$ is a random variable, then for any $t > 0$, we have

$$P(Y \geq t) \leq \frac{E(Y)}{t}$$

Proof. We notice that $t \cdot \mathbb{1}_{\{Y \geq t\}} \leq Y$, it is easily to prove. If $x \in \{Y \geq t\}$, then $t \cdot \mathbb{1}_{\{Y \geq t\}}(x) = t \leq Y(x)$, otherwise $t \cdot \mathbb{1}_{\{Y \geq t\}}(x) = 0 \leq Y(x)$, so by monotone of the expectation

$$E[t \cdot \mathbb{1}_{\{Y \geq t\}}] = tE[\mathbb{1}_{\{Y \geq t\}}] = tP(Y \geq t)$$

■

Theorem 1.5 (Tchebychev)

Suppose that $Y : \Omega \rightarrow \mathbb{R}$ is a random variable in $L^2(\Omega)$ (square integrable), then for any $t > 0$ we have

$$P(|Y - E[Y]| \geq t) \leq \frac{V(Y)}{t^2}$$

Proof. We apply Markov to prove it, we can estimate

$$\begin{aligned} P(|Y - E[Y]| \geq t) &= P((Y - E[Y])^2 \geq t^2) \\ &\leq \frac{E[(Y - E[Y])^2]}{t^2} \\ &= \frac{V(Y)}{t^2} \end{aligned}$$

■

Theorem 1.6 (Cantelli)

Suppose that $Y : \Omega \rightarrow \mathbb{R}$ is a random variable in $L^2(\Omega)$ (square integrable), then for any $t > 0$ we have

$$\begin{aligned} P(Y - E[Y] \geq t) &\leq \frac{V(Y)}{V(Y) + t^2} \\ P(|Y - E[Y]| \geq t) &\leq \frac{2V(Y)}{V(Y) + t^2} \end{aligned}$$

Proof. The proof of the inequality need to use inequality: for any $a, b > 0$,

$$P(X \geq a) \leq \frac{E[(X + b)^2]}{(a + b)^2} \tag{1}$$

We write $P(X \geq a) = E[\mathbb{1}_{\{X \geq a\}}]$, then we just need to prove $\mathbb{1}_{\{X \geq a\}} \leq (\frac{X+b}{a+b})^2$. For any $w \in \{X \geq a\}$, we have $(\frac{X+b}{a+b})^2(w) \geq (\frac{a+b}{a+b})^2 = 1 = \mathbb{1}_{\{X \geq a\}}(w)$, otherwise will conclude $(\frac{X+b}{a+b})^2 \geq 0$, so the inequality 1 is valid.

For prove the Cantelli, we let $Z = \frac{Y-E[Y]}{\sigma(Y)}$, then by above inequality

$$\begin{aligned} P(Y \geq t) &\leq \frac{E[(Y+b)^2]}{(t+b)^2} \\ &= \frac{E[Y^2] + 2bE[Y] + b^2E[1]}{(t+b)^2} \\ &= \frac{1+b^2}{(t+b)^2} \end{aligned}$$

We can put $b = 1/t$, then $\frac{1+b^2}{(t+b)^2} = \frac{1}{1+t^2}$, and then rewrite the inequality we get $P(Y - E[Y] \geq t) \leq \frac{V(Y)}{V(Y)+t^2}$. and notice that

$$P(Y - E[Y] \leq -t) = P((-Y) - E[-Y] \geq t)$$

and $V(-Y) = V(Y)$ implies the same upper bound, so we finish the proof. ■

The importance of the three inequalities is the estimation of the upper bound of some probability, if we can know the the expected value, we can get an upper bound

by Markov; if we also know the variance, a more precise upper bound can be given by Tchebychev and Cantelli.

Cantelli's inequality is a work based on the Tchebychev's inequality, if we rewrite the Tchebychev's inequality by take $t = \sigma(Y)t$, then we have

$$P(|X - \mu| \leq \sigma t) \geq \frac{1}{t^2}$$

Which always appears in the some statistical object like confidence interval, but it is a two-side interval estimation. If we rewrite Cantelli's inequality similarly:

$$P(X - \mu \leq \sigma t) \geq \frac{1}{1 + t^2}$$

$$P(|X - \mu| \leq \sigma t) \geq \frac{2}{1 + t^2}$$

We can find that Cantelli's inequality can do one-side estimation and it provides a worse bound then Tchebychev's when $t \geq \sigma$.

2 Classic analysis theory and technic

2.1 Power series and analytic function

This section contains Three parts:

- overview for power series and the important result
- real analytic function and Abel's theorem
- the superiority of the holomorphic function

Power series is a special case of the series of the function, it gives by the following sequence:

$$f_n : D \rightarrow \mathbb{C}, \quad z \mapsto a_n z^n$$

more general, we can write it as the form $a_n(z - z_0)^n$, but notice that we can just change variable by $u = z - z_0$, it is a translation, so clearly a diffeomorphism. In above statement D denote the domain where the series will be well-defined, i.e. convergent, so here needs a clear definition.

Lemma 2.1 (Abel's Lemma)

Given a complex-valued sequence $(a_n)_{n \in \mathbb{N}}$, if there exists $z_0 \in \mathbb{C}$ such that $(a_n z_0^n)_{n \in \mathbb{N}}$ is bounded, then we can conclude that

-If $|z| < |z_0|$, then power series $\sum_{n \in \mathbb{N}} a_n z^n$ converge.

-If $|z| < |z_0|$, then power series $\sum_{n \in \mathbb{N}} a_n z^n$ diverge.

Proof. The bounded sequence implies a real number M such that $a_n z_0^n \leq M$, so

$$|a_n z^n| = |a_n z_0^n \cdot \frac{z^n}{z_0^n}| \leq M \left| \frac{z}{z_0} \right|^n$$

so clearly the power series converge if $|z| \leq |z_0|$ by M-test.

If $|z| > |z_0|$, then $(a_n z^n)_{n \in \mathbb{N}}$ is not bounded, so immediately it can't converge to zero, so the power series diverge. ■

The lemma inspires us that the domain is nearly a disk, although we can not determine the convergence of the boundary, but we can formally define the **radius of convergence** of a power series $\sum_{n \in \mathbb{N}} a_n z^n$ is given by

$$R = \sup\{r \geq 0 \mid (a_n r^n)_{n \in \mathbb{N}} \text{ is bounded}\}$$

and we call $D = D(0, R)$ the **domain of convergence**. A more simple form of the radius of convergence is given by Cauchy and d'Alembert:

$$1/R = \limsup |a_n|^{1/n} = \lim \left| \frac{a_{n+1}}{a_n} \right|$$

and we convented here $1/0 = \infty$ and $1/\infty = 0$.

The convergence of the power series provides a good case of function, analytic function, which is the theme of the next section. We put function

$$f : \overline{D(0, r)} \rightarrow \mathbb{C}, \quad dz \mapsto \sum_{n \in \mathbb{N}} a_n z^n$$

where $r \in (0, R)$, and we suppose here $R > 0$. The function will be well-defined and continous since $z \mapsto a_n z^n$ is always uniformly continous on a compact set, so we can conclude that f is well-defined and continous on domaine convergence when we take $r \rightarrow R$. We will take about the derivable of the power series, it is a important property.

Theorem 2.2 (Derivable)

The power series $f(z) = \sum_{n \in \mathbb{N}} a_n z^n$ defined on the domaine $D(0, R)$ with raduis $R > 0$, then the derivative of f is also a power sereies with the same raduis of convergence and has the form

$$f'(z) = \sum_{n \in \mathbb{N}} n a_n z^{n-1}$$

Proof. ■

An immediate result is that power series is a holomorphic function, and another result is an inversion of the process, that means if we know a function definitely is converged by some power series in some domain, then we can write each coefficient in terms of the derivative of the function, usually in calculus we call it the Taylor's Formula.

Corollary (Taylor's series)

If $f(z)$ is the sum of the power series $\sum_{n \in \mathbb{N}} a_n z^n$ on the domain $D(0, R)$ with $R > 0$, then we have

$$a_n = \frac{f^{(n)}(0)}{n!}.$$

Proof. Manipulate above theorem to f k times we get

$$f^{(k)}(x) = \sum_{n \in \mathbb{N}} n(n-1) \cdots (n-k+1) a_n z^{n-k}$$

and we put $z = 0$, then we get $n!a_n = f^{(k)}(0)$, that is what we want. ■

we can also conclude the **analytic continuation** about the power series, although it can be got direct from holomorphic function, but the proof here is easy and it gives us the connection.

Corollary Suppose that $\sum_{n \in \mathbb{N}} a_n z^n$ and $\sum_{n \in \mathbb{N}} b_n z^n$ are two power series with the positive radius R_1 and R_2 , if there exists an voisinage of zero V such that $\sum_{n \in \mathbb{N}} a_n z^n = \sum_{n \in \mathbb{N}} b_n z^n$, then $a_n = b_n$ for any $n \in \mathbb{N}$.

Proof. We Let $f(z) = \sum_{n \in \mathbb{N}} a_n z^n$ and $g(z) = \sum_{n \in \mathbb{N}} b_n z^n$ on domaine, then we have

$$0 = (f - g)(z) = \sum_{n \in \mathbb{N}} (a_n - b_n) z^n$$

on the subset of the domaine V , so we applying above theorem we can get that

$$a_n - b_n = n!(f - g)(0) = 0$$

Which is the result we get, ■

After some basic description of power series, we can define the **analytic function**,

Definition 2.1 Let $\mathbb{K} = \mathbb{R}$ or \mathbb{C} , U is a open set in \mathbb{K} , a function $f : U \rightarrow \mathbb{K}$ is an analytic function if for any $z_0 \in U$, the function can be converged by a power series in a small voisinage of z_0 .

formally speaking, for any $z_0 \in U$, there exists $r > 0$ and a sequence $(a_n)_{n \in \mathbb{N}}$

such that in the domain $D(z_0, r) \subset U$ we have

$$f(z) = \sum_{n \in \mathbb{N}} a_n (z - z_0)^n$$

Remark a power series defined on a domain is clearly an analytic function, the choice of r can be formulated by $\min\{|z_0|, R - |z_0|\}$, where R is the radius of convergence.

The classic discussion about the analytic function is that whether analytic is a smooth function (C^∞), and conversely a smooth function is a analytic function? In the time of Abel, analysis is focused on \mathbb{R} , and a smooth function is usually considered to do expansion by Taylor's Formula, so the question in \mathbb{R} is equivalent to the question that for each smooth function whether its Taylor series converges to itself or not. In conclusion, the relation show as following in \mathbb{R}

$$\text{analytic function} \subset C^\infty \text{smooth function}$$

Proposition 2.3 (infinitely differentiable)

For any analytic function defined on an open set of \mathbb{K} , it is infinitely differentiable and its derivative is still an analytic function.

Proof. We let $f : U \rightarrow \mathbb{K}$, and take $a \in U$, the analytic function implies a positive $r > 0$ and a sequence (a_n) , such that $f(z) = \sum a_n(z - a)^n$ for any $z \in D(a, r)$, then applying theorem 2.2 we can conclude that

$$f^{(k)} = k!a_k$$

for any $k \in \mathbb{N}$, hence it is infinitely differentiable. What's more, for any $z \in D(a, r)$, $f'(z) = \sum n a_n(z - a)^{n-1}$ by the same theorem, which guarantee that the derivative is still an analytic function. ■

Now we will give an example that a real-value function is smooth but not analytic to finish our conclusion.

Example 2.1 we consider the following real function

$$f : \mathbb{R} \rightarrow \mathbb{R}, \quad x \mapsto \begin{cases} e^{-1/x^2} & x \neq 0 \\ 0 & x = 0 \end{cases}$$

Notice that $x \mapsto e^{-1/x^2}$ is a C^∞ function for any $x \neq 0$, and we can prove by recurrence that its n -times derivative has the form

$$f^{(n)}(x) = \frac{P_n(x)}{x^{3n}} e^{-1/x^2}$$

where $P_n \in \mathbb{R}[x]$. Then calculate the limite by changing $u = 1/x$, we know

$$\lim_{x \rightarrow 0} \frac{e^{-1/x^2}}{x^{3n}} = \lim_{u \rightarrow \infty} \frac{u^{3n}}{e^{u^2}} = 0$$

so for any $n \in \mathbb{N}$, $f^{(n)}(0)$ tends to zero, so we expend the function by adding $f^{(n)}(0) = 0$ such that $f \in C^\infty(\mathbb{R})$.

Suppose that f is analytics at $x = 0$, then we can write the Talyor's series at the voinsinage of zero

$$f(x) = \sum_{n \in \mathbb{N}} \frac{f^{(n)}(0)}{n!} x^n = 0$$

which means the function equals to null in the voisinage, clearly absurd since the series is not convergent to itself. Hence, f can not be analytic at zero although it is a smooth function.

Another work of Abel is about the convergence on the boundary of domaine of convergence, we give it here the version in \mathbb{R} .

Theorem 2.4 (Abel's Theorem)

Let $f(z) = \sum_{n \in \mathbb{N}} a_n z^n$ be a power seriees defined on a domaine $(-R, R)$ and $R > 0$. If the power series converges at $z = R$ (or $z = -R$), then the f is continous (one-sid)

at $z = R$ (or $z = -R$). Or simply, the theorem is equivalent to prove that

$$\lim_{r \rightarrow 1^-} \sum_{n \in \mathbb{N}} a_n r^n = \sum_{n \in \mathbb{N}} a_n$$

if $\sum_{n \in \mathbb{N}} a_n$ is a convergent series.

Proof. the rigorous proof needs to use the **summation by parts formula**:

$$\sum_{n=M}^N a_n b_n = a_N B_N - a_M B_{M-1} - \sum_{n=M}^{N-1} (a_{n+1} - a_n) B_n$$

where a_n and b_n are all finite, and $B_n = \sum_{k=1}^n b_k$ with convention $B_0 = 0$. ■

Finally i will talk about holomorphic function. Loosely speaking, holomorphic function is just the differentiable functions in \mathbb{C} , why do we not just call them "a differentiable function" and give them a special name? The important reason is the crazy regularity of the complex-valued function. By **Cauchy's integral formula**, for any open set containing an open disc D , if a function f is holomorphic in the open set, then for any $z \in D$

$$f(z) = \frac{1}{2\pi i} \int_{\partial D} \frac{f(\zeta)}{\zeta - z} d\zeta$$

then by caculation

$$\frac{f(z+h) - f(z)}{h} = \frac{1}{2\pi i} \int_{\partial D} \frac{f(\zeta)}{(\zeta - z)(\zeta - z - h)} d\zeta$$

By the continuity of the parametric integration at $h = 0$, we can conclude that f has derivatice and $f'(z) = \frac{1}{2\pi i} \int_{\partial D} \frac{f(\zeta)}{(\zeta - z)^2} d\zeta$, hence we can prove by recurrence that f is infinitely times diffrenetiable and with the form

$$f^{(n)}(z) = \frac{n!}{2\pi i} \int_{\partial D} \frac{f(\zeta)}{(\zeta - z)^{n+1}} d\zeta \quad (2)$$

That is an amazing result and also a fundamental theorem for complex analysis, so clearly, any holomorphic function is a C^∞ function, also the most important points is that the high-order derivative only depends on the original function. We recall the theorem 2.2, then we can complete the connection between analytic function and a smooth function in \mathbb{C} :

analytic function \iff holomorphic function

Theorem 2.5 (Stein 4.4)

If f is holomorphic function in an open set $\Omega \subset \mathbb{C}$, then f is an analytic function in Ω .

Proof. By definition, we just need to verify that in any $z_0 \in \Omega$, there exists a voisinage such that the Talyor's serieies $\sum_{n \in \mathbb{N}} \frac{f^{(n)}(z_0)}{n!} (z - z_0)^n$ converges to f .

Too see that we notice in Cauchy integration formula

$$\frac{1}{\zeta - z} = \frac{1}{\zeta - z_0} \frac{1}{1 - u}$$

by taking $u = \frac{z - z_0}{\zeta - z_0}$, then for any $|u| < 1$, we can rewrite formula as the form

$$f(z) = \frac{1}{2\pi i} \int_{\partial D} \frac{f(\zeta)}{\zeta - z_0} \sum_{n \in \mathbb{N}} u^n d\zeta = \sum_{n \in \mathbb{N}} \frac{(z - z_0)^n}{2\pi i} \int_{\partial D} \frac{f(\zeta)}{(\zeta - z_0)^{n+1}} d\zeta$$

Here interchange \int / \sum can be done since the holomorphic function is continous. and take equation 2 into above equality then we can get the result we hope. ■

Remark That means for any holomorphic function, we can do expansion casually.

2.2 Limit superior and limit inferior

A direct question from **Bolzano-Weierstrass theorem** is that how to determiner the range of the vlaue which the convergent subsequence converges to? Gnenerally, the sequence can be classified into three types: convergent, divergent and oscillation.

We take a real sequence $(a_n)_{n \in \mathbb{N}}$ and define a set

$$A_k = \{a_{k+p} | p \in \mathbb{N}\}$$

it means a set which contains the terms of sequence except a_0, \dots, a_{k-1} , then we define two new sequence by

$$v_n = \sup A_n, \quad w_n = \inf A_n$$

Notice that $A_{k+1} \subset A_k$ for any k , so clearly we have

$$w_n \leq w_{n+1} \leq a_{n+1} \leq v_{n+1} \leq v_n$$

for any n . Here w_n is an increasing sequence and v_n is a decreasing sequence, **so highly likely they will be convergent**. If $(a_n)_{n \in \mathbb{N}}$ is a convergent sequence, clearly as $n \rightarrow \infty$, v_n and w_n will converge to the limit of a_n , but if $(a_n)_{n \in \mathbb{N}}$ is oscillated, the convergence will change. See the example below:

Example 2.2 *We define a sequence as following*

$$a_n = \begin{cases} \frac{1}{n} & n \equiv 0 \pmod{3} \\ \frac{1}{n} + 1 & n \equiv 1 \pmod{3} \\ \frac{1}{n} + 2 & n \equiv 2 \pmod{3} \end{cases}$$

we calculate the first 6 terms of v_n and w_n

$$w_1 = w_2 = \dots = w_6 = 0$$

$$v_1 = v_2 = 3/2, v_3 = v_4 = v_5 = 1/5 + 2, v_6 = 1/7 + 2$$

so we can conclude with a little work that w_n converges to 0, and v_n converges to 2.

In above example, we easily guess that all possible values the subsequence will converge to are 0, 1, 2, so w_n and v_n seem to give the superimum and infimum respectively, hence we formally define the limit superior and limit inferior of a sequence $(a_n)_{n \in \mathbb{N}}$ by

$$\limsup a_n := \inf(\sup_{k \geq 0} A_k)$$

$$\liminf a_n := \sup(\inf_{k \geq 0} A_k)$$

we conclude the properties as folloing

Proposition 2.6 *For a general real number $\mathbb{R} \cup \{\pm\infty\}$, we define $(a_n)_{n \in \mathbb{N}}$ is a sequence of \mathbb{R} , then for any subsequence $(a_{n_k})_{k \in \mathbb{N}}$ which converges to L , then*

$$\liminf a_n \leq L \leq \limsup a_n.$$

In another words, all adherence points of the sequence will be in $[\liminf a_n, \limsup a_n]$.

Proof. ■

Here we give an application in probability theory about sequence of the events.

Theorem 2.7 (Borel-Cantelli Lemma) *Suppose $(A_i)_{i \in \mathbb{N}}$ is a sequence of events in a probability space (Ω, \mathcal{T}, P) , then*

(a) If $\sum_{n \in \mathbb{N}} P(A_i) < +\infty$, then the probability that infinitely many of them occur is zero.

(b) If $\sum_{n \in \mathbb{N}} P(A_i) = +\infty$ and the events are independent, then the probability that infinitely many of them occur is 1.

we need to translate the language into the measure theory. here "the probability that infinitely many of them occur" can be equivalent to the statement below: almost all $w \in \Omega$ will be in infinitely many of the events $\{A_i\}$. we use the limit superior and inferior to formalize the statement

$$\limsup A_i = \bigcap_{N \in \mathbb{N}} \bigcup_{i \geq N} A_i$$

here we firstly prove that

$$\limsup A_i = \{w \in \Omega \mid w \text{ is in infinitely many of events}\}$$

for any $w \in \limsup A_i$, $w \in \cup_{i \geq 0} A_i$, so there exists $x_0 \in \mathbb{N}$ such that $w \in A_{x_0}$. Then we consider $w \in \cup_{i \geq x_0+1} A_i$, so there exists $x_1 \geq x_0 + 1$ such that $w \in A_{x_1}, \dots$, by recurrence we can conclude a strictly increasing map of integer $n \mapsto x_n$, then we can conclude that $w \in \cap_{n \in \mathbb{N}} A_{x_n}$.

For another hand, if w in infinitely many of evnets, then we label all the events where it occurs, and it will be countable, so there exists a correspondence with \mathbb{N} and we denote it by f , then $w \in \cap_{n \in \mathbb{N}} A_{f(n)} \subset \limsup A_i$.

So we can conclude Borel-Cantelli Lemma by the measure theory as following:

- (a) $\sum_{n \in \mathbb{N}} P(A_i) < +\infty \implies P(\limsup A_i) = 0$.
- (b) $\sum_{n \in \mathbb{N}} P(A_i) = +\infty \wedge \text{independence} \implies P(\limsup A_i) = 1$.

So finally we finish the proof of theorem:

Proof. we notice that

$$w \mapsto \#\{i \in \mathbb{N} | w \in A_i\}$$

is a measurable function by discrete measure, and then we notice that

$$\begin{aligned}\int_{\Omega} \#\{i \in \mathbb{N} | w \in A_i\} dP &= \int_{\Omega} \sum_{n \in \mathbb{N}} \mathbb{1}_{A_i} dP \\ &= \sum_{n \in \mathbb{N}} P(A_i)\end{aligned}$$

so if $\sum_{n \in \mathbb{N}} P(A_i) < +\infty$, then $\#\{i \in \mathbb{N} | w \in A_i\}$ must be almost finite, i.e. almost all $w \in \Omega$ occur in finite many of events, so $\limsup A_i = 0$.

If $\sum_{n \in \mathbb{N}} P(A_i) = +\infty$, by independence we have

$$P(\cup_{i=N}^M A_i^c) = \prod_{i=N}^M 1 - P(A_i^c) \leq e^{-\sum_{i=N}^M P(A_i)}$$

as $M \rightarrow \infty$ we can know that $P(\cap_{i \geq N} A_i^c) = 0$ for any N , then by De Morgan's Law

$$P(\limsup A_i) = P((\cup_{N \in \mathbb{N}} \cap_{i \geq N} A_i^c)^c) = 1 - 0 = 1$$

■

3 Complex analysis

3.1 Holomorphic Function

Complex-valued function is a function defined on \mathbb{C} , formally it is

$$f : \mathbb{C} \rightarrow \mathbb{C}, \quad z \mapsto f(z)$$

\mathbb{C} can be seen same as \mathbb{R}^2 in view of \mathbb{R} –vector space, so there exists a correspondence with two real variable functions.

For any z , there exists $u, v \in \mathbb{R}$ such that $f(z) = u + iv$, then

$$u = \frac{1}{2}(f(z) + \overline{f(z)}), \quad v = \frac{1}{2i}(f(z) - \overline{f(z)})$$

so by taking all z , we can get two functions from \mathbb{C} to \mathbb{R} , and we just identify $z \in \mathbb{C}$ with $(x, y) \in \mathbb{R}^2$ by $z = x + iy$, then

$$f(z) = f(x + iy) = f(x, y) = u(z) + iv(z) = (u(x, y), v(x, y))$$

Here we should notice that \mathbb{R}^2 equips the norm $\|\cdot\|_2$ to make it compatible.

Notice that \mathbb{C} naturally has the norm structure, so it makes sense to define its differentiation directly from the topology:

Definition 3.1 Let Ω be an open set of \mathbb{C} , a function $f : \Omega \rightarrow \mathbb{C}$ is called holomorphic at $z_0 \in \Omega$ if the limit

$$\lim_{h \rightarrow 0} \frac{f(z_0 + h) - f(z_0)}{h}$$

exists. We use $H(\Omega)$ to denote the set of all holomorphic functions on Ω .

Example 3.1 An important example that a complex-valued function is not holomorphic is $z \mapsto \bar{z}$. We observe the function at $z = 0$

$$\frac{\overline{z+h} - \bar{z}}{h} = \frac{\bar{h}}{h} = \frac{re^{-a}}{re^a} = e^{-2a}$$

so the limit does not exist. By if we rewrite the function in real variables by $(x, y) \mapsto (x, -y)$, then clearly the jacobian matrix is $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, which means the function is always differentiable in \mathbb{R}^2 , so here difference appears and we can realize that the differentiation of complex-value function is a little different from.

Although the two types of differentiation is not the same thing, is there some connection between them? Let us firstly consider a set of differential operators:

$$\begin{cases} x = \frac{z+\bar{z}}{2} \\ y = \frac{z-\bar{z}}{2i} \end{cases} \implies \begin{cases} \frac{\partial}{\partial z} = \frac{\partial}{\partial x} \frac{\partial x}{\partial z} + \frac{\partial}{\partial y} \frac{\partial y}{\partial z} = \frac{1}{2} \left(\frac{\partial}{\partial x} - i \frac{\partial}{\partial y} \right) \\ \frac{\partial}{\partial \bar{z}} = \frac{\partial}{\partial x} \frac{\partial x}{\partial \bar{z}} + \frac{\partial}{\partial y} \frac{\partial y}{\partial \bar{z}} = \frac{1}{2} \left(\frac{\partial}{\partial x} + i \frac{\partial}{\partial y} \right) \end{cases}$$

Suppose f is a complex-value function holomorphic at 0 with $f(0) = 0$, then

$$f(z) = L(z) + o(z) = ax + by + o(z) = \frac{a - ib}{2}z + \frac{a + ib}{2}\bar{z} + o(z)$$

with L a \mathbb{C} -linear map with $a, b \in \mathbb{C}$ and $z = x + iy$, then by above operators we know that

$$\frac{f(z)}{z} = \frac{\partial f}{\partial z}(0) + \frac{\partial f}{\partial \bar{z}}(0) \cdot \frac{\bar{z}}{z} + \frac{o(z)}{z}$$

if the limit exists as z tends to zero, then the term having $\frac{\bar{z}}{z}$ must vanish, that means $\frac{\partial f}{\partial \bar{z}} = 0$, that is the necessary condition that f is holomorphic at $z = 0$.

Furthermore, if we merely view \mathbb{C} as \mathbb{R}^2 to write function as the form of linear combination by two real-value functions $f = u + iv$, then we can conclude the Jacobien matrix

$$J_f(x, y) = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{pmatrix}$$

Then $L(z)$ can be viewed as vector (x, y) operates on $J_f(x, y)$, and notice that $L(z) = k \cdot z$ form some $k \in \mathbb{C}$ and \mathbb{C} is isomorphic to a subspace of $M_2(\mathbb{R})$ with the form $\begin{pmatrix} a & -b \\ b & a \end{pmatrix}$, so immediately the jacobi matrix has the same form and we get a relation

: Cauchy-Riemann Equation:

$$\begin{cases} \frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x} \end{cases}$$

Let us reflect the procedure above, the different things is that L must be a \mathbb{C} –linear map instead of \mathbb{R} –linear map, which is crucial.

Lemma 3.1 *Let $V = \text{Lin}(\mathbb{R}^2, \mathbb{C})$ be the set of all linear maps from \mathbb{R}^2 to \mathbb{C} , then*

- (1) V is a \mathbb{R} –vector space with $dx : (x, y) \mapsto x$ and $dy : (x, y) \mapsto y$ as the base.*
- (2) $dz = dx + idy$ and $d\bar{z} = dx - idy$ compose another base of V*
- (3) V is a \mathbb{C} –vector space if and only if for any $L \in V$ under the base dz and $d\bar{z}$, the coefficient of $d\bar{z}$ is zero.*

Proof. (1) For any $L \in V$, we have $L(x, y) = x \cdot L(1, 0) + y \cdot L(0, 1)$ notice that dx and dy actually are in V , and $dx(x, y) = x$, $dy(x, y) = y$, then $L = L(1, 0)dx + L(0, 1)dy$ with $L(1, 0), L(0, 1) \in \mathbb{C}$.

(2) we take $c_1 dz + c_2 d\bar{z} = 0$, then $(c_1 + c_2)dx + i(c_1 - c_2)dy = 0$, which implies $c_1 = c_2 = 0$, so dz and $d\bar{z}$ are linearly independent.

(3) Take $f = adz + bd\bar{z} \in V$ and $u \in \mathbb{C}^2$

$$\begin{aligned} f(iu) - if(u) &= adz(iu) + bd\bar{z}(iu) - iad\bar{z}(u) - ibd\bar{z}(u) \\ &= -2bu_y \end{aligned}$$

The result must be zero since the map is linear over \mathbb{C} , then $b = 0$. ■

Let us consider differential

$$df : U \rightarrow \text{Lin}(\mathbb{R}^2, \mathbb{C})$$

notice that in differential $L(1, 0) = Df(a, b)(1, 0) = f_x(a, b)$, so we have that

$$df = f_x dx + f_y dy$$

Now if we expect to write df as the combination of dz and $d\bar{z}$, so

$$df = \mu dz + \lambda d\bar{z} = (\mu + \lambda)dx + i(\mu - \lambda)dy$$

with calculation we have that

$$\mu = \frac{f_x - if_y}{2}, \quad \lambda = \frac{f_x + if_y}{2}$$

Which implies the differential operators like above.

So we can conclude the fundamental theorem of holomorphic function.

Theorem 3.2 Suppose that $f = u + iv$ is a complex function with u, v two functions of class $C^1(\mathbb{R}^2, \mathbb{R})$, then following statements are equivalent.

(1) f is holomorphic on Ω .

(2) $\frac{\partial f}{\partial \bar{z}} = 0$ on Ω .

(3) Cauchy-Riemann Equation is satisfied.

Proof. (2) f is holomorphic, then for any $z_0 \in \Omega$, $df(z_0)$ must be a \mathbb{C} -linear map in $\text{Lin}(\mathbb{R}^2, \mathbb{C})$, so the coefficient of $d\bar{z}$ must be zero by above lemma, and notice that the coefficient is just $\frac{\partial f}{\partial \bar{z}}(z_0)$.

(3) Just calculate

$$\begin{aligned} 0 &= \frac{\partial f}{\partial \bar{z}} = \frac{1}{2} \left(\frac{\partial f}{\partial x} + i \frac{\partial f}{\partial y} \right) \\ &= \frac{1}{2} \left(\frac{\partial u + iv}{\partial x} + i \frac{\partial u + iv}{\partial y} \right) \\ &= \frac{1}{2} \left[\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right) + i \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] \end{aligned}$$

■