

Full Notes

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1 Friday January 10

Recall that \mathbb{C} is a field, where $z = x + iy \implies \bar{z} = x - iy$, and if $z \neq 0$ then $z^{-1} = \bar{z}/|z|^2$.

Lemma (Triangle Inequality): $|z + w| \leq |z| + |w|$

Proof:

$$(|z| + |w|)^2 - |z + w|^2 = 2(|z\bar{w}| - \Re z\bar{w}) \geq 0.$$

Lemma (Reverse Triangle Inequality): $||z| - |w|| \leq |z - w|$.

Proof:

$$|z| = |z - w + w| \leq |z - w| + |w| \implies |w| - |z| \leq |z - w| = |w - z|.$$

Claim: $(\mathbb{C}, |\cdot|)$ is a normed space.

Definition: $\lim z_n = z \iff |z_n - z| \rightarrow 0 \in \mathbb{R}$.

Definition: A disc is defined as $D_r(z_0) := \{z \in \mathbb{C} \mid |z - z_0| < r\}$, and a subset is open iff it contains a disc. By convention, D_r denotes a disc about $z_0 = 0$.

Definition: $\sum_k z_k$ converges iff $S_N := \sum_{|k| < N} z_k$ converges.

Note that $z_n \rightarrow z$ and $z_n = x_n + iy_n$, if $|z_n - z| = \sqrt{(x_n - x)^2 + (y_n - y)^2} < \varepsilon$ then $|x - x_n|, |y - y_n| < \varepsilon$.

Since \mathbb{R} is complete iff every Cauchy sequence converges iff every bounded monotone sequence has a limit.

Note: This is useful precisely when you don't know the limiting term.

Note that $\sum_k z_k$ thus converges if $\left| \sum_{k=m}^n z_k \right| < \varepsilon$ for m, n large enough, so sums converges iff they have small tails.

Definition: $\sum z_k$ converges absolutely iff $\sum |z_k|$ converges.

Note that the partial sums $\sum_{k=1}^N |z_k|$ are monotone, so $\sum |z_k|$ converges iff the partial sums are bounded above.

Definition: A sum of the form $\sum_{k=0}^{\infty} a_k z_k$ is a power series.

Examples

$$\sum x^k = \frac{1}{1-x}$$

$$\sum (-x^2)^k = \frac{1}{1+x^2}.$$

Note that both of these have a radius of convergence equal to 1, since the first has a pole at $x = 1$ and the second as a pole at $x = i$.

2 Monday January 13th

Recall that $\sum z_k$ converges iff $s_n = \sum_{k=1}^n z_k$ converges.

Lemma: Absolute convergence implies convergence.

The most interesting series: $f(z) = \sum a_k z^k$, i.e. power series.

Divergence lemma: If $\sum z_k$ converges, then $\lim z_k = 0$.

Corollary: If $\sum z_k$ converges, $\{z_k\}$ is uniformly bounded by a constant $C > 0$, i.e. $|z_k| < C$ for all k .

Proposition: If $\sum a_k z_k$ converges at some point z_0 , then it converges for all $|z| < |z_0|$.

The inequality is necessarily strict. For example, $\sum \frac{z^{n-1}}{n}$ converges at $z = -1$ (alternating harmonic series) but not at $z = 1$ (harmonic series).

Proof: Suppose $\sum a_k z_1^k$ converges. The terms are uniformly bounded, so $|a_k z_1^k| \leq C$ for all k . Then we have $|a_k| \leq C/|z_1|^k$, so if $|z| < |z_1|$, we have $|a_k z^k| \leq |z|^k \frac{C}{|z_1|^k} = C(|z|/|z_1|)^k$. So if $|z| < |z_1|$, the parenthesized quantity is less than 1, and the original series is bounded by a geometric series. Letting $r = |z|/|z_1|$, we have

$$\sum |a_k z^k| \leq \sum C r^k = \frac{C}{1-r},$$

and so we have absolute convergence. ■

Exercise (future problem set): Show that $\sum \frac{1}{k} z^{k-1}$ converges for all $|z| = 1$ except for $z = 1$. (Use summation by parts.)

Definition The radius of convergence is the real number R such that $f(z) = \sum a_k z^k$ converges precisely for $|z| < R$ and diverges for $|z| > R$. We denote a disc of radius R centered at zero by D_R .

If $R = \infty$, then f is said to be *entire*.

Proposition: Suppose that $\sum a_k z^k$ converges for all $|z| < R$. Then $f(z) = \sum a_k z^k$ is continuous on D_R , i.e. using the sequential definition of continuity, $\lim_{z \rightarrow z_0} f(z) = f(z_0)$ for all $z_0 \in D_R$.

Recall that $S_n(z) \rightarrow S(z)$ uniformly on Ω iff $\forall \varepsilon > 0$, there exists a $M \in \mathbb{N}$ such that $n > M \implies |S_n(z) - S(z)| < \varepsilon$ for all $z \in \Omega$

Note that arbitrary limits of continuous functions may not be continuous. Counterexample: $f_n(x) = x^n$ on $[0, 1]$; then $f_n \rightarrow \delta(1)$. Note that it uniformly converges on $[0, 1 - \varepsilon]$ for any $\varepsilon > 0$.

Exercise: Show that the uniform limit of continuous functions is continuous.

Hint: Use the triangle inequality.

Proof of proposition: Write $f(z) = \sum_{k=0}^N a_k z^k + \sum_{k=N+1}^{\infty} a_k z^k := S_N(z) + R_N(z)$. Note that if $|z| < R$, then there exists a T such that $|z| < T < R$ where $f(z)$ converges uniformly on D_T .

Check!

We need to show that $|R_N(z)|$ is uniformly small for $|z| < s < T$. Note that $\sum a_k z^k$ converges on D_T , so we can find a C such that $|a_k z^k| \leq C$ for all k . Then $|a_k| \leq C/T^k$ for all k , and so

$$\begin{aligned}
\left| \sum_{k=N+1}^{\infty} a_k z^k \right| &\leq \sum_{k=N+1}^{\infty} |a_k| |z|^k \\
&\leq \sum_{k=N+1}^{\infty} (c/T^k) s^k \\
&= c \sum_{k=N+1}^{\infty} |s/T|^k \\
&= c \frac{r^{N+1}}{1-r} \\
&= C \varepsilon_n \rightarrow 0,
\end{aligned}$$

which follows because $0 < r = s/T < 1$.

So $S_N(z) \rightarrow f(z)$ uniformly on $|z| < s$ and $S_N(z)$ are all continuous, so $f(z)$ is continuous.

There are two ways to compute the radius of convergence:

- Root test: $\lim_k |a_k|^{1/k} = L \implies R = \frac{1}{L}$.
- Ratio test: $\lim_k |a_{k+1}/a_k| = L \implies R = \frac{1}{L}$.

As long as these series converge, we can compute derivatives and integrals term-by-term, and they have the same radius of convergence.

3 Wednesday January 15th

See references: Taylor's Complex Analysis, Stein, Barry Simon (5 volume set), Hormander (technically a PDEs book, but mostly analysis)

Good Paper: Hormander 1955

We'll mostly be working from Simon Vol. 2A, most problems from from Stein's Complex.

3.1 Topology and Algebra of \mathbb{C}

To do analysis, we'll need the following notions:

1. Continuity of a complex-valued function $f : \Omega \rightarrow \mathbb{C}$
2. Complex-differentiability: For $\Omega \subset \mathbb{C}$ open and $z_0 \in \Omega$, there exists $\varepsilon > 0$ such that $D_\varepsilon = \{z \mid |z - z_0| < \varepsilon\} \subset \Omega$, and f is **holomorphic** (complex-differentiable) at z_0 iff

$$\lim_{h \rightarrow 0} \frac{1}{h} (f(z_0 + h) - f(z_0))$$

exists; if so we denote it by $f'(z_0)$.

Example: $f(z) = z$ is holomorphic, since $f(z+h) - f(z) = z+h - z = h$, so $f'(z_0) = \frac{h}{h} = 1$ for all z_0 .

Example: Given $f(z) = \bar{z}$, we have $f(z+h) - f(z) = \bar{h}$, so the ratio is $\frac{\bar{h}}{h}$ and the limit doesn't exist (?).

We say f is holomorphic on an open set Ω iff it is holomorphic at every point, and is holomorphic on a closed set C iff there exists an open $\Omega \supset C$ such that f is holomorphic on Ω .

If f is holomorphic, writing $h = h_1 + ih_2$, then the following two limits exist and are equal:

$$\begin{aligned} \lim_{h_1 \rightarrow 0} \frac{f(x_0 + iy_0 + h_1) - f(x_0 + iy_0)}{h_1} &= \frac{\partial f}{\partial x}(x_0, y_0) \\ \lim_{h_2 \rightarrow 0} \frac{f(x_0 + iy_0 + ih_2) - f(x_0 + iy_0)}{ih_2} &= \frac{1}{i} \frac{\partial f}{\partial y}(x_0, y_0) \\ &\implies \frac{\partial f}{\partial x} = \frac{1}{i} \frac{\partial f}{\partial y}. \end{aligned}$$

So if we write $f(z) = u(x, y) + iv(x, y)$, we have

$$\frac{\partial u}{\partial x} + i \frac{\partial v}{\partial x} \Big|_{(x_0, y_0)} = \frac{1}{i} \left(\frac{\partial u}{\partial y} + i \frac{\partial v}{\partial y} \right) \Big|_{(x_0, y_0)},$$

and equating real and imaginary parts yields the Cauchy-Riemann equations:

$$\begin{aligned} \frac{\partial u}{\partial x} + i \frac{\partial v}{\partial x} &= -i \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} \\ \iff \frac{\partial u}{\partial x} &= \frac{\partial v}{\partial y} \quad \text{and} \quad \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x}. \end{aligned}$$

The usual rules of derivatives apply:

1. $(\sum f)' = \sum f'$

Proof: Direct.

2. $(\prod f)' = \text{product rule}$

Proof: Consider $(f(z+h)g(z+h) - f(z)g(z))/h$ and use continuity of g at z .

3. Quotient rule

Proof: Nice trick, write $q = \frac{f}{g}$ so $qg = f$, then $f' = q'g + qg'$ and $q' = \frac{f'}{g} - \frac{fg'}{g^2}$.

4. Chain rule

Proof: Use the fact that if $f'(g(z)) = a$, then

$$f(z+h) - f(z) = ah + r(z, h), \quad |r(z, h)| = o(|h|) \rightarrow 0.$$

Write $b = g'(z)$, then

$$f(g(z+h)) = f(g(z) + bh + r_1) = f(g(z)) + f'(g(z))bh + r_2$$

by considering error terms, and so

$$\frac{1}{h}(f(g(z+h)) - f(g(z))) \rightarrow f'(g(z))g'(z)$$

4 Appendix

Collection of facts used on problem sets

Standard forms of conic sections:

- Circle: $x^2 + y^2 = r^2$
- Ellipse: $\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$
- Hyperbola: $\left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2 = 1$
 - Rectangular Hyperbola: $xy = \frac{c^2}{2}$.
- Parabola: $-4ax + y^2 = 0$.

Mnemonic: Write $f(x, y) = Ax^2 + Bxy + Cy^2 + \dots$, then consider the discriminant $\Delta = B^2 - 4AC$:

- $\Delta < 0 \iff$ ellipse
 - $\Delta < 0$ and $A = C, B = 0 \iff$ circle
- $\Delta = 0 \iff$ parabola
- $\Delta > 0 \iff$ hyperbola

Completing the square:

$$x^2 - bx = (x - s)^2 - s^2 \quad \text{where } s = \frac{b}{2}$$

$$x^2 + bx = (x + s)^2 - s^2 \quad \text{where } s = \frac{b}{2}.$$

Properties of complex numbers

- $\Re(z) = \frac{1}{2}(z + \bar{z})$ and $\Im(z) = \frac{1}{2i}(z - \bar{z})$.
- $z\bar{z} = |z|^2$