1 Basic Knowledge

HCV Note

Useful Complex Number Properties: $|Re(z)|, |Im(z)| \le |z|$ $\quad Re(z) = \frac{z+\overline{z}}{2}, Im(z) = \frac{z-\overline{z}}{2i}, |z|^2 = z\overline{z}$

Triangle (Reverse) Inequality: $|z_1 + z_2| \le |z_1| + |z_2|$ $\quad \big||z_1| - |z_2|\big| \le |z_1 - z_2|$ $\quad (Re(zw) = 0 \Leftrightarrow \overline{zw} = -zw; Im(zw) = 0 \Leftrightarrow zw = \overline{zw})$

Argument: $\arg(z) := \{\theta : z = |z|e^{i\theta}\} = \{Arg(z) + 2\pi k : k \in \mathbb{Z}\}$ **Principle Value of Argument**: $Arg(z) \in (-\pi, \pi]$

· **Operations on Argument**: $arg(z_1 z_2) = arg(z_1) + arg(z_2)$ $\quad arg\left(\frac{z_1}{z_2}\right) = arg(z_1) - arg(z_2)$ $\quad arg(\overline{z}) = -arg(z)$

2 Holomorphic Functions

2.1 Open/Closed Set | Limit Point | limit of Sequence | Continuous of Function

Open/Closed/Punctured ε-disc: $D_\varepsilon(z_0) := \{z \in \mathbb{C} : |z - z_0| < \varepsilon\}$ $\quad \overline{D}_\varepsilon(z_0) := \{z \in \mathbb{C} : |z - z_0| \le \varepsilon\}$ $\quad D'_\varepsilon(z_0) := \{z \in \mathbb{C} : 0 < |z - z_0| < \varepsilon\}$

Open/Closed Set in $\mathbb{C}$: $U \subset \mathbb{C}$ is **open** if $\forall z_0 \in U, \exists \varepsilon > 0, D_\varepsilon(z_0) \subseteq U$ $\quad U$ is **closed** if $\mathbb{C} \setminus U$ is open **Lemma**: $D_\varepsilon, D'_\varepsilon$ open, $\overline{D}_\varepsilon$ closed.

Limit Point of S: $z_0 \in \mathbb{C}$ is a limit point of S if: $\forall \varepsilon > 0, D'_\varepsilon(z_0) \cap S \ne \emptyset$ 聚点 **Bounded**: S is bounded if $\exists M > 0$ s.t. $|z| \le M, \forall z \in S$

Closed of Set S: $\overline{S} :=$ 所有 S 的 limit point 和 S 的点. **Property**: Let $S \subseteq \mathbb{C}$, then S is closed $\Leftrightarrow S = \overline{S}$.

Limit of sequence: Sequence $(z_n)_{n\in\mathbb{N}}$ has limit z if $\forall \varepsilon > 0, \exists N \in \mathbb{N}$ s.t. $\forall n \ge N \Rightarrow |z_n - z| < \varepsilon$. limit rules 依旧成立

1. **Lemma|Important**: $\lim z_n = z \Leftrightarrow \lim Re(z_n) = Re(z)$ and $\lim Im(z_n) = Im(z)$
2. **Cauchy**: Sequence $(z_n)_{n\in\mathbb{N}}$ is cauchy if: $\forall \varepsilon > 0, \exists N \in \mathbb{N}$ s.t. $\forall m, n \ge N \Rightarrow |z_m - z_n| < \varepsilon$ **Lemma**: Cauchy $\Leftrightarrow$ convergent.
3. **Lemma|Closed of Set**: $S \subseteq \mathbb{C}, z \in \mathbb{C}. \Rightarrow [\ z \in \overline{S} \Leftrightarrow \exists$ sequence $(z_n)_{n\in\mathbb{N}} \in S$ s.t. $\lim z_n = z\ ]$
4. **Bolzano-Weierstrass**: Every bounded sequence in $\mathbb{C}$ has a convergent subsequence.

Complex Functions: $\forall f : \mathbb{C} \to \mathbb{C}$ we can write it as: $f(z) = f(x + iy) = u(x, y) + iv(x, y)$ where $u, v : \mathbb{R}^2 \to \mathbb{R}$

Limit of Function: $a_0 \in \mathbb{C}$ is the limit of f at z_0 if: $\forall \varepsilon > 0, \exists \delta > 0$ s.t. $0 < |z - z_0| < \delta \Rightarrow |f(z) - a_0| < \varepsilon$ limit rules 依旧成立

· **Lemma|Important**: $\lim_{z\to z_0} f(z) \Leftrightarrow \lim_{(x,y)\to(x_0,y_0)} u(x, y) = Re(a_0)$ and $\lim_{(x,y)\to(x_0,y_0)} v(x, y) = Im(a_0)$

· **Useful Formula**: $\lim_{z\to z_0} g(\overline{z}) = \lim_{z\to\overline{z_0}} g(z)$

continuous of Function: f is continuous at z_0 if: $\forall \varepsilon > 0, \exists \delta > 0$ s.t. $|z - z_0| < \delta \Rightarrow |f(z) - f(z_0)| < \varepsilon$ continuous rules 依旧成立

1. **Lemma|Important**: f is continuous at $z_0 \Leftrightarrow u, v$ are continuous at (x_0, y_0)
2. **'Extreme Value Theorem'**: f is continuous on a closed and bounded set $S \subseteq \mathbb{C}$, then $f(S)$ is closed and bounded.
3. **Lemma|continuous⇔open**: f is continuous $\Leftrightarrow \forall$ open set U, preimage $f^{-1}(U) := \{z \in \mathbb{C} | f(z) \in U\}$ is open.

2.2 Differentiable | Holomorphic Function | C-R Equation

Differentiable: Let $z_0 \in \mathbb{C}$ and $U \subseteq \mathbb{C}$ be neighborhood of z_0, then $f : U \to \mathbb{C}$ is differentiable at z_0 if: $\lim_{z\to z_0} \frac{f(z)-f(z_0)}{z-z_0}$ exists.

· **I.** f is differentiable $\Rightarrow f$ is continuous. **II. Holomorphic** $\Leftrightarrow$ Differentiable + neighborhood (除非是一个点时不成立,$|z|$) diff rules + chain rule 成立

Cauchy-Riemann Equations: If $z_0 = x_0 + iy_0, f(z) = u(x, y) + iv(x, y)$ is differentiable at $z_0 \Rightarrow u_x = v_y, v_x = -u_y$ **at** (x_0, y_0).

· If $z_0 = x_0 + iy_0, f = u + iv$ satisfies: $^1u, v$ are *continuously differentiable* on a neighborhood of (x_0, y_0) and:

$^2u, v$ satisfies Cauchy-Riemann Equations at (x_0, y_0). $\Rightarrow f$ is differentiable at z_0.

· ps: 常见可导复数函数: $\exp(z), \sin z, \cos z, \log z, z^\alpha$, polynomial, sinh, cosh, $\Gamma(z)$, $|z|^2$ (at 0), constant ps: 常见不可导复数函数: $\overline{z}, |z| \cdot \overline{z}, Re(z), Im(z), \mathrm{Arg}(z)$

Harmonic Function: $h : \mathbb{R}^2 \to \mathbb{R}$ is harmonic if: $\forall (x, y) \in \mathbb{R}^2$ $\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0$ (**Laplace Equation**)

· **Lemma**: If $f = u + iv$ is holomorphic on $\mathbb{C}$ and u, v are twice *continuously differentiable*, $\Rightarrow u, v$ are harmonic.

Harmonic Conjugate: Let $u, v : U \to \mathbb{R}, U \subseteq \mathbb{R}^2$ be harmonic functions. u, v are harmonic conjugate if: $f = u + iv$ is holomorphic on U.

Properties of Polynomial: The domain of rational function and polynomial are always open. **Lemma**: If $P(z_0) = 0$ then $P(\overline{z_0}) = 0$

First-order Operator ∂: $\partial := \frac{1}{2}\left(\frac{\partial}{\partial x} - i\frac{\partial}{\partial y}\right)$ $\quad \overline{\partial} := \frac{1}{2}\left(\frac{\partial}{\partial x} + i\frac{\partial}{\partial y}\right)$ $\quad ||$ $\quad f = u + iv$ satisfies C-R Equations $\Leftrightarrow \overline{\partial} f = 0$

sin/cos Functions: $\sin z := \frac{e^{iz}-e^{-iz}}{2i}$ $\quad \cos z := \frac{e^{iz}+e^{-iz}}{2}$ **Exponential Function**: $\exp(z) = e^x(\cos(y) + i\sin(y))$

1. $\sin(x + iy) = \sin x \cosh y + i \cos x \sinh y$ $\quad \cos(x + iy) = \cos x \cosh y - i \sin x \sinh y$
2. $\sin(z + w) = \sin(z)\cos(w) + \cos(z)\sin(w)$ $\quad \cos(z + w) = \cos(z)\cos(w) - \sin(z)\sin(w)$
3. $\sin^2 z + \cos^2 z = 1$ $\quad \sin(z + \frac{\pi}{2}) = \cos(z)$ $\quad \sin(z + 2k\pi) = sin(z)$ $\quad \cos(z + 2k\pi) = \cos(z)$ $\quad \star\sin z, \cos z$ NOT bounded.

Hyperbolic Functions: $\sinh z := \frac{\exp(z)-\exp(-z)}{2}$ $\quad \cosh z := \frac{\exp(z)+\exp(-z)}{2}$ $\quad ||$ $\quad \sinh(iz) = i\sin z$ $\quad \cosh(iz) = \cos z$

Logarithm: Define *multivalued function*: $\log z := \{w \in \mathbb{C} : \exp w = z\}$ **Principal Branch**: $Log(z) := \ln|z| + iArg(z)$

1. **I.** $\log(z) = \ln|z| + i\arg z = \{\ln|z| + iArg(z) + i2\pi k : k \in \mathbb{Z}\}$ **II.** $\log(zw) = \log(z) + \log(w)$ **III.** $\log(1/z) = -\log(z)$
2. **Branch of Logarithm**: $Log_\phi(z) := \ln|z| + iArg_\phi(z)$ $\quad Log_\phi(z)$ is holomorphic on D_ϕ
3. If $g : U \to \mathbb{C}$, then $Log_\phi(g(z))$ is holomorphic on $g^{-1}(D_\phi) \cap U$
4. $Log(z)$ *not continuous* on $\mathbb{C}$. $\quad Log(z)$ not continuous on $Re(z) \le 0, Im(z) = 0$.

Branch Cut|Cut Plane: *Branch Cut* $L_{z_0,\phi} := \{z \in \mathbb{C} : z = z_0 + re^{i\phi}, r \ge 0\}$ *Cut Plane*: $D_{z_0,\phi} := \mathbb{C} \setminus L_{z_0,\phi}$ $\quad L_\phi = L_{0,\phi}; D_\phi = D_{0,\phi}$

Branch of Argument: $Arg_\phi(z) := z$ 的辐角, 但是角度限制在: $\phi < Arg_\phi(z) \le \phi + 2\pi$. ps: $Arg_{-\pi}(z) = Arg(z)$

$f(z)$	$f'(z)$	$f(z)$	$f'(z)$	$f(z)$	$f'(z)$	$f(z)$	$f'(z)$	$f(z)$	$f'(z)$	$f(z)$	$f'(z)$	$f(z)$	$f'(z)$
z^n	nz^{n-1}	$\exp(z)$	$\exp(z)$	$\sin(z)$	$\cos(z)$	$\cos(z)$	$-\sin(z)$	$\sinh(z)$	$\cosh(z)$	$\cosh(z)$	$\sinh(z)$	$\log_\phi z$	$\frac{1}{z}$ $_{z \in D_\phi}$

Complex Powers: $z^\alpha := \{\exp(\alpha w) : w \in \log(z)\} = \{\exp[\alpha(\ln|z| + iArg(z) + i2k\pi)] : k \in \mathbb{Z}\}$ $\quad \frac{d}{dz} z^\alpha = \alpha z^{\alpha-1}$ $_{z \in D_\phi}$

I. If $\alpha \in \mathbb{Z}$, there is one value of z^α **II.** If $\alpha = \frac{p}{q}, \gcd(p, q) = 1, p, q \in \mathbb{Z}, q \ne 0$, there are exactly q values of z^α

III. If α is *irrational* or *non-real*, there are infinitely values z^α **IV.** $1^{1/q}, q \in \mathbb{Z}, q \ne 0$ is $\{1, w, ..., w^{q-1}\}, w = \exp(i2\pi/q)$

V. We prefer use $\exp(z)$ to denote single-valued function, and e^z to denote multi-valued function.

Principal Branch: $z^\alpha := \exp(\alpha Log(z))$ **Operation**: $z^\alpha z^\beta = z^{\alpha+\beta}$ (Using Principal Branch) **NB**: $(z_1 z_2)^\alpha \ne z_1^\alpha z_2^\alpha$; $(z^\alpha)^\beta \ne z^{\alpha\beta}$