

Introductory Complex Analysis Cheat Sheet

Field of Complex Numbers

We construct the field of complex numbers in the following quotient ring, $\mathbb{C} = \mathbb{R}[i]/(i^2 + 1)$.

Algebra of Complex Numbers

- Addition: $(a + bi) + (c + di) = (a + c) + (b + d)i$
- Multiplication: $(a + bi)(c + di) = (ac - bd) + (ad + bc)i$
- Division: $\frac{a + bi}{c + di} = \frac{(a + bi)(c - di)}{(c + di)(c - di)} = \frac{(ac + bd) + (bc - ad)i}{c^2 + d^2}$
- Square root: $\sqrt{a + bi} = z = \left(\sqrt{\frac{|a + bi| + a}{2}} + i \sqrt{\frac{|a + bi| - a}{2}} \right)$
- $\overline{a + bi} = a - bi$, $|a + bi|^2 = a^2 + b^2$

Conjugation, Absolute Value

- Complex conjugation:** $\overline{z + w} = \overline{z} + \overline{w}$
 $\overline{zw} = \overline{z}\overline{w}$
 $\overline{\overline{z}} = z$
 Geometrically, conjugation is reflection over the real axis.
- Absolute value:** $|z| = \sqrt{z\overline{z}}$
 $|z\overline{z}| = |z|^2$
 $|z + w|^2 = |z|^2 + |w|^2 + 2\operatorname{Re}(z\overline{w})$
 $|z - w|^2 = |z|^2 + |w|^2 - 2\operatorname{Re}(z\overline{w})$
 $|z + w|^2 + |z - w|^2 = 2(|z|^2 + |w|^2)$
 The absolute value function turns the metric on $\mathbb{C}$ to complete under this norm.

Basic Topological Definitions in $\mathbb{C}$

Some basic results:

- For $a_0 \in \mathbb{C}$, $r > 0$ we denote the ball (i.e. disk) of radius r around a_0 to be $B(a_0, r) = \{z \in \mathbb{C} : |z - a_0| < r\}$.
- A point $z \in \mathbb{C}$ is a **limit point** of $E \subseteq \mathbb{C}$ if $W \cap E \setminus \{z\} \neq \emptyset$ for every ball W centered at z .
- A subset $E \subseteq \mathbb{C}$ is said to be **open** if $z \in E$, $\exists r > 0$ s.t. $B(z, r) \subseteq E$.
- A subset $E \subseteq \mathbb{C}$ is said to be **closed**, if E^c is open in $\mathbb{C}$, or equivalently z is which contains all its limit points.

Some properties of open sets:

- $\mathbb{C}$ and $\emptyset$ are open subsets of $\mathbb{C}$.
- All finite intersections of open sets are open sets.
- The collection of all open sets on $\mathbb{C}$ form a topology on $\mathbb{C}$.

Interior, closure, density

- Interior:** Let $E \subseteq \mathbb{C}$. The interior of E is defined as, E° is set of all interior points of E , or equivalently, $\bigcup \{B(z, r) : B(z, r) \subseteq E\}$.
- Closure:** Let $E \subseteq \mathbb{C}$. The closure of E is defined as $\overline{E} = E \cup E'$ where E' is the set of all limit points of E .
- Density:** Let $E \subseteq \mathbb{C}$. The closure of E is $\mathbb{C}$. Then E is called dense in $\mathbb{C}$.

Path: A path is a metric space from a point $a \in \mathbb{C}$ to $b \in \mathbb{C}$ is a continuous mapping $\gamma : [0, 1] \rightarrow \mathbb{C}$ s.t. $\gamma(0) = a$ and $\gamma(1) = b$.

Separated and Connected

For a metric space (X, d) ,

- Separated:** X is separated if it disjoint non-empty open subsets A, B of X s.t. $X = A \cup B$.
- Connected:**
 - X is connected if it has no separation.
 - X is connected $\iff X$ does not contain a proper subset of X which is both open and closed in X .
 - Continuous functions preserve connectedness.
 - An open subset $U \subseteq \mathbb{C}$ is connected $\iff$ for $z, w \in U$, there exists a path from z to w .

Basic Topological definitions in $\mathbb{C}$ space

Open (event): Let (X, d) be a metric space and E be a collection of open sets in X . We say that E is an open event if a subset $K \subseteq E$, if $K \subseteq \bigcup \{W : W \in E\}$. **Consequences:** For subset $K \subseteq X$ is compact if for every open cover E of K , there exists $E_0, \dots, E_n \in E$ s.t. $K \subseteq \bigcup_{i=0}^n E_i$. i.e. K is compact if it has a finite open cover.

- In a metric space, a compact set is closed.
- A closed subset of a compact set is closed.

Limit point compact: We say a metric space X is limit point compact if every infinite subset of X has a limit point.

- If X is a compact metric space, then it is also limit point compact.

Sequentially compact: We say a metric space X is sequentially compact if every sequence has a convergent subsequence.

- If X is limit point compact then X is sequentially compact.
- Let X be sequentially compact, then X is a compact metric space.

Lebesgue number lemma: Let X be sequentially compact, and let $\mathcal{W}$ be an open cover of X . Then $\exists \delta > 0$ s.t. for $z \in X$, $\exists z \in W$ s.t. $B(z, \delta) \subseteq W$.

Isometries on the Complex Plane

A function $f : \mathbb{C} \rightarrow \mathbb{C}$ is called an **isometry** if $|f(z) - f(w)| = |z - w|$, $\forall z, w \in \mathbb{C}$.

- Let f be an isometry s.t. $f(0) = 0$, then the linear product $\langle f(z), f(w) \rangle = \langle z, w \rangle$, $\forall z, w \in \mathbb{C}$.
- If f is an isometry s.t. $f(0) = 0$ then f is a linear map.
- The standard isometry for $z = a + bi \in \mathbb{C}$, $\arg(z + bi) = \tan^{-1} \frac{b}{a}$.

Functions on the Complex Plane

Uniform convergence: Let $M \subseteq \mathbb{C}$ and $f_0, \dots, f_n : M \rightarrow \mathbb{C}$ be a set of functions on M . We say, $\{f_n\}_{n=0}^\infty$ converges uniformly to f if given $\epsilon > 0$, for $N \in \mathbb{N}$ s.t. $|f_n(z) - f(z)| < \epsilon$, $\forall n \geq N$ and $z \in M$.

Complex exponential: For $z \in \mathbb{C}$, $\exp(z) = \sum_{n=0}^\infty \frac{z^n}{n!}$.

Trigonometric functions: For $z \in \mathbb{C}$, $\cos(z) = \frac{\exp(iz) + \exp(-iz)}{2}$ and $\sin(z) = \frac{\exp(iz) - \exp(-iz)}{2i}$.

Hyperbolic trigonometric functions: For $z \in \mathbb{C}$, $\cosh(z) = \frac{\exp(z) + \exp(-z)}{2}$ and $\sinh(z) = \frac{\exp(z) - \exp(-z)}{2}$.

Complex Differentiability

Complex differentiable: Let $U \subseteq \mathbb{C}$ and $f : U \rightarrow \mathbb{C}$, we say that f is complex differentiable at a point $z_0 \in U$ if z_0 is an interior point and the following limit exists $\lim_{z \rightarrow z_0} \frac{f(z) - f(z_0)}{z - z_0}$. The limit is denoted as $f'(z_0)$ or $\frac{df}{dz}$.

Bi-holomorphic functions: If $f : U \rightarrow \mathbb{C}$ is complex differentiable at every point $z \in U$, then f is said to be a bi-holomorphic on U . **Entire functions:** Functions which are complex differentiable on $\mathbb{C}$ are called entire functions.

- Complex differentiability implies continuity.
- Complex derivatives of a function are linear transformations.
- Product rule:** If $f, g : U \rightarrow \mathbb{C}$ are complex differentiable at $z_0 \in U$. Then fg is complex differentiable at z_0 with derivative $f'(z_0)g(z_0) + f(z_0)g'(z_0)$.
- Quotient rule:** If $f, g : U \rightarrow \mathbb{C}$ are complex differentiable at $z_0 \in U$, and g doesn't vanish at z_0 . Then $\left(\frac{f}{g}\right)'(z_0) = \frac{f'(z_0)g(z_0) - f(z_0)g'(z_0)}{g(z_0)^2}$.
- Chain rule:** If $f : U \rightarrow \mathbb{C}$ and $g : D \rightarrow U$ are complex differentiable at $z_0 \in D$, and $f'(g(z_0)) \neq 0$. Then $g'(z_0)f'(g(z_0)) = f'(f(g(z_0)))$.

Power Series

Formal Power Series: A formal power series around $z_0 \in \mathbb{C}$ is a formal expression $\sum_{n=0}^\infty a_n(z - z_0)^n$, where $a_n \in \mathbb{C}$ and z is indeterminate.

Radius of convergence: For a formal power series $\sum_{n=0}^\infty a_n(z - z_0)^n$ the radius of convergence $R \in [0, \infty]$ given by $R = \lim_{n \rightarrow \infty} |a_n|^{-1/n}$. Using the ratio test is identical (i.e. $R = \lim_{n \rightarrow \infty} \left| \frac{a_n}{a_{n+1}} \right|$).

- The series converges absolutely when $z \in B(z_0, R)$, and for $z \in R$, the series converges uniformly, else if $z = z_0 + R$ the series diverges.
- Let $z \in \mathbb{C}$ s.t. $|z - z_0| = R$, then $\exists$ infinitely many $n \in \mathbb{N}$ s.t. $|a_n|^{1/n} \rightarrow |z - z_0|$.

Abel's Theorem: Let $f(z) = \sum_{n=0}^\infty a_n(z - z_0)^n = a_0 + \dots$ be a power series with a positive radius of convergence R , suppose $z_1 = z_0 + R e^{i\theta}$ for a point $\theta \in \mathbb{R}$, $f(z_1)$ converges. Then $\lim_{z \rightarrow z_1} f(z) = a_0 + \dots = f(z_1)$.

Differentiation of Power Series

Let $f(z) = \sum_{n=0}^\infty a_n(z - z_0)^n = a_0 + \dots$ be a power series around z_0 with a radius of convergence R . Then f is **holomorphic** in $B(z_0, R)$.

- $f'(z) = \sum_{n=1}^\infty n a_n(z - z_0)^{n-1}$ with same radius of convergence R .
- $a_n = \frac{f^{(n)}(z_0)}{n!}$

Cauchy product of two power series: For power series $f(z) = \sum_{n=0}^\infty a_n(z - z_0)^n$ and $g(z) = \sum_{n=0}^\infty b_n(z - z_0)^n$ with degree of convergence at least R . Then the Cauchy product $f(z)g(z) = \sum_{n=0}^\infty c_n(z - z_0)^n$ where $c_n = \sum_{k=0}^n a_k b_{n-k}$ also has degree of convergence at least R .

Cauchy-Riemann Differential Equations

For a complex function $f(z) = u(x, y) + i v(x, y)$,

$$f'(z) = \frac{\partial f}{\partial z} = \frac{\partial u}{\partial x} + i \frac{\partial v}{\partial x} = \frac{\partial u}{\partial z} + i \frac{\partial v}{\partial z}$$

Therefore, we get the two **Cauchy-Riemann Differential equations**,

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}, \quad \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x}$$

A function is **holomorphic** if it satisfies the Cauchy-Riemann equations.

Wirtinger Derivatives:

$$\frac{\partial}{\partial z} = \frac{1}{2} \left(\frac{\partial}{\partial x} + i \frac{\partial}{\partial y} \right), \quad \frac{\partial}{\partial \bar{z}} = \frac{1}{2} \left(\frac{\partial}{\partial x} - i \frac{\partial}{\partial y} \right)$$

If f is holomorphic at z_0 then $\frac{\partial f}{\partial \bar{z}} = 0$ and $f'(z_0) = \frac{\partial f}{\partial z}(z_0) = \frac{\partial f}{\partial z}(z_0)$.

Harmonic Functions

Laplace's Delta: $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$.

Harmonic functions: Let $u : U \rightarrow \mathbb{R}$ be a twice differentiable function. We say that u is a harmonic function if $\Delta u = 0$.

For any holomorphic function f , $u(x, y), v(x, y)$ are examples of harmonic functions, but there are harmonic functions which are not holomorphic.

Boundary of a set: For a metric space $(X, d) \in \mathbb{R}$,

the boundary of $U = \partial U = \overline{U} \setminus U$.

Maximum principle for harmonic functions: Let $u : U \rightarrow \mathbb{R}$ be a twice differentiable harmonic function. Let $K \subseteq U$ be a compact sub set of U . Then, $\max_{K \cap U} u(x) = \max_{\partial K \cap U} u(x)$ and $\min_{K \cap U} u(x) = \min_{\partial K \cap U} u(x)$.

Maximum principle for holomorphic functions: Let $U \subseteq \mathbb{C}$ be open and connected and let $f : U \rightarrow \mathbb{C}$ be a holomorphic function. Then, for compact $K \subseteq U$, we have, $\max_{K \cap U} |f(z)| = \max_{\partial K \cap U} |f(z)|$.

Harmonic conjugates: Let $u : U \rightarrow \mathbb{R}$ be a twice differentiable harmonic function. We say that $v : U \rightarrow \mathbb{R}$ is a harmonic conjugate of u if $f = u + iv$ is holomorphic.

- For a harmonic function from $\mathbb{C}$ to $\mathbb{R}$, there exists a uniquely determined harmonic conjugate from $\mathbb{C}$ to $\mathbb{R}$ (up to constant).

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Judd E. Hollander



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