MAT354 Lecture Notes

Arky!! :3c

'25 Fall Semester

Contents

§1 Day 1: Recap of Preliminaries

We start by discussing the complex plane and complex numbers. Given $z \in \mathbb{C}$, we say that $\Re(z)$ and $\Im(z)$ are the real and imaginary parts of z respectively, i.e., $z = x + iy$. $\mathbb{C}$ is the set of all complex numbers. In this manner, we may identify $z = x + iy$ with $(x, y) \in \mathbb{R}^2$ using the standard complex plane.

(a) The complex *conjugate* of z is given by $\bar{z} = x - iy$, where we have that

$$\Re(z) = \frac{z + \bar{z}}{2}, \qquad \Im(z) = \frac{z - \bar{z}}{2i}.$$

(b) We now define addition and mlutiplication for the complex numbers. For all $z_1 = x_1 + iy_1$ and $z_2 = x_2 + iy_2$, we have that

$$\begin{aligned} z_1 + z_2 &= (x_1 + x_2) + i(y_1 + y_2), \\ z_1 z_2 &= (x_1 + iy_1)(x_2 + iy_2) \\ &= x_1x_2 + ix_1y_2 + iy_1x_2 + i^2 y_1y_2 = (x_1x_2 - y_1y_2) + i(x_1y_2 + y_1x_2). \end{aligned}$$

We have that $(\mathbb{C}, +, \times)$ is a field, with $(\mathbb{R}, +, \times)$ as a subfield. To verify this, we need to check that it indeed satisfies:

- Commutativity; for all $z_1, z_2 \in \mathbb{C}$, we have that $z_1 + z_2 = z_2 + z_1$ and $z_1 z_2 = z_2 z_1$.
- Associativity: for all $z_1, z_2, z_3 \in \mathbb{C}$, we have that $(z_1 + z_2) + z_3 = z_1 + (z_2 + z_3)$ and $(z_1 z_2) z_3 = z_1 (z_2 z_3)$.
- Distributivity: for all $z_1, z_2, z_3 \in \mathbb{C}$, we have that $z_1(z_2 + z_3) = z_1 z_2 + z_1 z_3$.

(c) The absolute value of a complex number $z = x + iy$ is given by $|z| = \sqrt{x^2 + y^2}$. In particular, this yields the triangle inequality, where for any $z, w \in \mathbb{C}$, we have that $|z + w| \leq |z| + |w|$. The proof either comes visually or through explicit computation, both of which I will not write out here for brevity.[1]

As an extension of the inequality, we also automatically have that

$$|\Re z| \leq |z|, \qquad |\Im z| \leq |z|,$$

and that for all $z, w \in \mathbb{C}$, we have

$$||z| - |w|| \leq |z - w|.$$

Proof. Using the triangle inequality, we have that

$$\begin{aligned} |z| &= |(z - w) + w| \leq |z - w| + |w|, \\ |w| &= |(w - z) + z| \leq |z - w| + |z|, \end{aligned}$$

of which both imply that $|z| - |w| \leq |z - w|$ and $|w| - |z| \leq |z - w|$. $\square$

For any $z \in \mathbb{C}$, we have that $|z|^2 = z \cdot \bar{z}$.

Proof. Write $z = x + iy$; then $|z|^2 = x^2 + y^2$, where we may note that $z \cdot \bar{z} = (x + iy)(x - iy)$ which yields the right hand side of the earlier equation through expansion. $\square$

[1] no full credit if you draw a picture on the exam lmao

Finally, for $z, w \in \mathbb{C}$, we have that $|zw| = |z|\,|w|$. This is left as an exercise to the student.

(d) The polar form of a nonzero complex number $z \neq 0$ is given by $z = \gamma e^{i\theta}$, where $\gamma > 0$ and $\theta \in \mathbb{R}$. Let us assume the Euler formula; for all $\theta \in \mathbb{R}$, we have that

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

Let $r = |z|$; we have that $|z| = \left|re^{i\theta}\right| = |r|\left|e^{i\theta}\right| = r \cdot 1 = r$. θ is the angle between the positive real axis to the half-line starting from 0 and passing through z. In this manner, $z = re^{i\theta} = |z|(\cos\theta + i\sin\theta) = |z|\cos\theta + i\,|z|\sin\theta$, which means we have that

$$\Re z = |z|\cos\theta, \qquad \Im z = |z|\sin\theta.$$

As an example, let us find all the complex numbers z such that $z^4 = i$. Since $i = e^{i\frac{\pi}{2}}$, $z = \rho e^{i\theta}$ satisfying $z^4 = i$ becomes $\rho^4 e^{i\cdot 4\theta} = e^{i\frac{\pi}{2}}$, meaning

$$\begin{cases} \rho^4 = 1, \\ 4\theta = \frac{\pi}{2} + 2k\pi, \quad k \in \mathbb{Z}. \end{cases}$$

This means $\rho = 1$ and $\theta = \frac{\pi}{8} + \frac{k\pi}{2}$, where $k \in \mathbb{Z}$. Considering the cases $k = 0, 1, 2, 3$ and observing that there are only 4 equivalence classes modulo 4 to consider, we have that

$$z_0 = e^{i\frac{\pi}{8}}, \quad z_1 = e^{i\frac{5\pi}{8}}, \quad z_2 = e^{i\frac{9\pi}{8}}, \quad z_3 = e^{i\frac{13\pi}{8}}.$$

We now discuss convergence. We say that a set of complex numbers $\{z_n\}_{n\in\mathbb{N}}$ converges to $w \in \mathbb{C}$ if $\lim_{n\to\infty} |z_n - w| = 0$. We write it as $\lim_{n\to\infty} z_n = w$. In the complex plane, the convergence can be in any direction.

Lemma 1.1. $\{z_n\}_{n\in\mathbb{N}}$ converges to w if and only if $\{\Re z_n\}_{n\in\mathbb{N}}$ converges to $\Re w$ and $\{\Im z_n\}_{n\in\mathbb{N}}$ converges to $\Im w$.

Proof. We have that

$$\begin{aligned} |z_n - w| &= |(\Re z_n - \Re w) + i(\Im z_n - \Im w)| \\ &\leq |\Re z_n - \Re w| + |\Im z_n - \Im w|, \end{aligned}$$

where as $n \to \infty$, we have that the right hand side is given by $0 + 0$. For the opposite direction, we have that $|z| \geq |\Re z|$ or $|\Im z|$, so we have that

$$|\Re z_n - \Re w| = |\Re(z_n - w)| \leq |z_n - w|,$$

which approaches 0 as $n \to \infty$. The same argument goes for the imaginary portion. ☐

A sequence of complex numbers $\{z_n\}_{n\in\mathbb{N}}$ is called *Cauchy* if $|z_n - z_m| \to 0$ as $n, m \to \infty$. In $\varepsilon - \delta$, this means that for all $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that $|z_n - z_m| < \varepsilon$ for all $n, m > N$.

Theorem 1.2 (Bolzano-Weierstrass Theorem)**.** $\mathbb{R}$ is *complete*, i.e., every Cauchy sequence of real numbers convergesto a real number.

Theorem 1.3. $\mathbb{C}$ is complete.

Proof. Take any Cauchy sequence of complex numbers $\{z_n\}$. Using the inequalities $|\Re z| \leq |z|$ and $\{\Im z\} \leq |z|$, we have that $\{\Re z_n\}$ and $\{\Im z_n\}$ are Cauchy sequences of real numbers. By Bolzano-Weierstrass, we have that $\Re z_n \to x_0 \in \mathbb{R}$ and $\Im z_n \to y_0 \in \mathbb{R}$. By the previous lemma, we actually have $\lim_{n\to\infty} z_n = x_0 + iy_0$. ☐

We now move onto topology in the complex plane. Given $z_0 \in \mathbb{C}$ and $r > 0$, we can form an open or closed disc centered at z_0 of radius r. We write both of these as

$$D_r(z_0) = \{z \in \mathbb{C} \mid |z - z_0| < r\},$$
$$\bar{D}_r(z_0) = \{z \in \mathbb{C} \mid |z - z_0| \leq r\},$$

Given a set $\Omega \subseteq \mathbb{C}$, a point z_0 is an interior point if there exists $r > 0$ such that $D_r(z) \subseteq \Omega$. The interior of Ω is given by the set of all such interior points. In particular, the interior of $\bar{D}_r(i)$ is $D_r(i)$.

A set Ω is called *open* if every point in Ω is an interior point. Ω is called *closed* if the complement of Ω, $\Omega^c = \mathbb{C} \setminus \Omega$, is open. As an example, the open right half-plane $\{z \in \mathbb{C} \mid \Re z > 0\}$ is open.

Proof. For any $z \in \Omega$, let $z = x + iy$, and take $r = \frac{x}{2} = \frac{\Re z}{2}$. Then we claim that $D_r(z) \subseteq \Omega$. For all $w \in D_r(z)$, we clearly have that

$$\Re w = \Re z - (\Re z - \Re w) \geq \Re z - |z - w| \geq \frac{\Re z}{2} > 0,$$

and so all such $w \in \Omega$, and we are done. □

A point $z \in \mathbb{C}$ is a *limit point* of Ω if there exists a sequence $\{z_n\} \subset \Omega$ with $z_n \neq z$ such that $z_n \to z$.

As an example, we define D to be the open unit disc centered at 0. 0 and 1 are both limit points of D, but 1 is not contained in D itself.[2] The *closure* of Ω, $\bar{\Omega}$, is given by Ω unioned with all its limit points. The *boundary* of a set Ω, wirtten $\partial\Omega$, is given by $\bar{\Omega} \setminus \operatorname{int} \Omega$. A set $\Omega \subseteq \mathbb{C}$ is said to be compact if it is closed and bounded, i.e., there exists $M > 0$ such that $|z| \leq M$ for all $z \in \Omega$.

Theorem 1.4. A set $\Omega \subseteq \mathbb{C}$ is compact if and only if every sequence $\{z_n\} \subset \Omega$ has a subsequence that converges to a point in Ω.

Proposition 1.5. If $\Omega_1 \supset \Omega_2 \cdots \supset \Omega_n \supset \ldots$ is a sequence of nonempty compact sets in $\mathbb{C}$, where $\operatorname{diam}(\Omega_n) = \sup_{z,w \in \Omega_n} |z - w| \to 0$ as $n \to \infty$, then there exists a unique $w \in \mathbb{C}$ such that $w \in \Omega_n$ for every $n \in \mathbb{N}$.

Proof. For each Ω_n, pick a point $z_n \in \Omega_n$. Then $\{z_n\}_{n \in \mathbb{N}}$ is a Cauchy sequence because the diameter of Ω_n approaches 0. By the Bolzano-Weierstrass theorem for complex numbers, this means that $\{z_n\}_{n \in \mathbb{N}}$ indeed does converge to some $w \in \mathbb{C}$. In particular, we have w is the limit of the subsequence $\{z_m\}_{m \geq n} \subseteq \Omega_n$, where Ω_n is compact, meaning the limit w should be in Ω_n. This means there exists a unique $w \in \mathbb{C}$ such that $w \in \Omega_n$ for every $n \in \mathbb{N}$.

To show the uniqueness of w, we argue by contradiction; assume $w' \neq w$ satisfies the property. Then $|w' - w| > 0$. Since $w, w' \in \Omega_n$ for all n, this contradicts that $\operatorname{diam}(\Omega_n) \to 0$. □

An open set Ω is called *connected* if it is not possible to find two disjoint nonempty open sets Ω_1 and Ω_2 such that $\Omega = \Omega_1 \cup \Omega_2$. A connected open set in $\mathbb{C}$ is called a *region*.

[2] hell is it disc or disk YKW LET'S COMPROMISE it's spelled disque actually (paint nails)