

Complex Analysis

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January 26, 2023

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Chapter 1

The Complex Numbers

1.1 The Field of Complex Numbers

Definition. We define the set of **complex numbers** to be the collection of all ordered pairs of real numbers $\mathbb{C} = \{(a, b) : a, b \in \mathbb{R}\}$ together with the binary operations $+$ and \cdot of **complex addition**, and **complex multiplication**, respectively defined by the rules

$$\begin{aligned}(a, b) + (c, d) &= (a + c, b + d) \\ (a, b)(c, d) &= (ac - bd, bc + ad)\end{aligned}$$

Theorem 1.1.1. *The set of complex numbers \mathbb{C} forms a field together with complex addition and complex multiplication.*

Corollary. \mathbb{C} is a field extension of the real numbers \mathbb{R} .

Proof. The map $a \rightarrow (a, 0)$ from $\mathbb{R} \rightarrow \mathbb{C}$ defines an imbedding of \mathbb{R} into \mathbb{C} . ■

Definition. We define the element $i = (0, 1)$ of \mathbb{C} so that $i^2 = -1$, and the polynomial $z^2 + 1$ has as root i . We write $(a, b) = a + ib$. If $z = a + ib$, we call a the **real part** of z , and b the **imaginary part** of z and write $\operatorname{Re} z = a$ and $\operatorname{Im} z = b$.

Definition. Let $z = a + ib \in \mathbb{C}$. We define the **norm** (or **modulus**) of z to be $\|z\| = \sqrt{a^2 + b^2}$. We define the complex **conjugate** of z to be $\bar{z} = a - ib$.

Lemma 1.1.2. *For every $z \in \mathbb{C}$, $\|z\|^2 = z\bar{z}$.*

Proof. Let $z = a + ib$. Then $\bar{z} = a - ib$, and so $z\bar{z} = (a + ib)(a - ib) = a^2 + b^2 = (\sqrt{a^2 + b^2})^2 = \|z\|^2$. ■

Corollary. *If $z \neq 0$, then $z^{-1} = \frac{1}{z} = \frac{\bar{z}}{\|z\|^2}$.*

Proof. The relation follows from above, and it remains to show that it is indeed the inverse element. Notice that if $z \in \mathbb{C}$ is nonzero, then $z \frac{\bar{z}}{\|z\|^2} = \frac{z\bar{z}}{\|z\|^2} = \frac{\|z\|^2}{\|z\|^2} = 1$. ■

Example 1.1. (1) Let $z = a + ib$. Then we get that $\frac{1}{z} = \frac{\bar{z}}{\|z\|^2}$ has real part $\operatorname{Re} \frac{1}{z} = \frac{a}{a^2 + b^2}$ and imaginary part $\operatorname{Im} \frac{1}{z} = -\frac{b}{a^2 + b^2}$.

- (2) Let $z = a + ib$, and $c \in \mathbb{R}$. Then $\frac{z-c}{z+c} = \operatorname{Re} \frac{z-c}{z+c}$, so $\operatorname{Im} \frac{z-c}{z+c} = 0$.
- (3) Let $z = a + ib$, then $z^3 = a^3 - 3ab^2 + i(3a^2b - b^3)$ So that $\operatorname{Re} z^3 = a^3 - 3ab^2$ and $\operatorname{Im} z^3 = 3a^2b - b^3$.
- (4) $\frac{3+i5}{1+i7} = \frac{19}{25} - i\frac{18}{25}$.
- (5) $(-\frac{1}{2} + i\frac{\sqrt{3}}{2})^3 = 1$, and hence $(-\frac{1}{2} + i\frac{\sqrt{3}}{2})^6 = 1$.
- (6) Notice that $i^n = 1, i, -1, -i$ whenever $n \equiv 0 \pmod{4}$, $n \equiv 1 \pmod{4}$, $n \equiv 2 \pmod{4}$, and $n \equiv 3 \pmod{4}$. respectively.
- (7) $\| -2 + i \| = \sqrt{5}$, and $\|(2+i)(4+i3)\| = \|5+i10\| = 5\sqrt{5}$.

Lemma 1.1.3. *The following are true for all $z, w \in \mathbb{C}$.*

- (1) $\operatorname{Re} z = \frac{1}{2}(z + \bar{z})$ and $\operatorname{Im} z = \frac{1}{2i}(z - \bar{z})$.
- (2) $\overline{(z + w)} = \bar{z} + \bar{w}$ and $\overline{zw} = \bar{z} \bar{w}$.
- (3) $\|\bar{z}\| = \|z\|$.

Proof. Let $z = a + ib$ and $w = c + id$. Then notice that

$$\frac{(a + ib) + (a - ib)}{2} = \frac{2a + (ib - ib)}{2} = \frac{2a}{2} = a = \operatorname{Re} z$$

and

$$\frac{(a + ib) - (a - ib)}{2i} = \frac{(a - a) + 2ib}{2} = \frac{2ib}{2i} = b = \operatorname{Im} z$$

Moreover

$$\overline{(a + ib) + (c + id)} = \overline{(a + c) + i(b + d)} = (a + c) - i(b + d) = (a - ib) + (c - id)$$

And

$$\overline{(a + ib)(c + id)} = \overline{(ac - bd) + i(bc + ad)} = (ac - bd) - i(bc + ad) = (a - ib)(c - id)$$

so that $\overline{z + w} = \bar{z} + \bar{w}$ and $\overline{zw} = \bar{z} \bar{w}$.

Now, we have that $\|zw\|^2 = (zw)\overline{zw} = (zw)(\bar{z} \bar{w}) = (z\bar{z})(w\bar{w}) = \|z\|^2\|w\|^2$. Taking square roots, we get the result

$$\|zw\| = \|z\|\|w\|$$

Finally, notice that $\|z\|^2 = z\bar{z} = \bar{\bar{z}}\bar{\bar{z}} = \|\bar{z}\|^2$. ■

Corollary. *The following are also true; provided $w \neq 0$.*

- (1) $\overline{\left(\frac{z}{w}\right)} = \frac{\bar{z}}{\bar{w}}$.
- (2) $\left\|\frac{z}{w}\right\| = \frac{\|z\|}{\|w\|}$

Corollary. *If $z = z_1 + \cdots + z_n$, and $w = w_1 \cdots w_n$, with $z_i, w_i \in \mathbb{C}$ for all $1 \leq i \leq n$, then*

$$(1) \quad \bar{z} = \bar{z}_1 + \cdots + \bar{z}_n.$$

$$(2) \quad \|w\| = \|w_1\| \cdots \|w_n\|.$$

Proof. We prove both results by induction on n . For $n = 2$, we have already shown that $\bar{z} = \bar{z}_1 + \bar{z}_2$ and $\|w\| = \|w_1\|\|w_2\|$. Now, for all $n \geq 2$, suppose that both

$$\begin{aligned} \bar{z} &= \bar{z}_1 + \cdots + \bar{z}_n \\ \|w\| &= \|w_1\| \cdots \|w_n\| \end{aligned}$$

Then let $z' = z + z_{n+1}$ and $w' = ww_{n+1}$ for $z_{n+1}, w_{n+1} \in \mathbb{C}$. Then we have that

$$\begin{aligned} z' &= z + z_{n+1} = z_1 + \cdots + z_n + z_{n+1} \\ w' &= ww_{n+1} = w_1 \cdots w_n w_{n+1} \end{aligned}$$

so by the induction hypothesis, we have

$$\bar{z'} = \overline{(z + z_{n+1})} = \bar{z} + \bar{z}_{n+1} = \bar{z}_1 + \cdots + \bar{z}_n + \bar{z}_{n+1}$$

and that

$$\|w'\| = \|ww_{n+1}\| = \|w\|\|w_{n+1}\| = \|w_1\| \cdots \|w_n\|\|w_{n+1}\|$$

which completes the proof. ■

Lemma 1.1.4. *Let $z \in \mathbb{C}$. Then z is a real number if, and only if $z = \bar{z}$.*

Proof. If z is real, then $z = a + i0$, for some $a \in \mathbb{R}$, and hence $\bar{z} = a - i0 = z$. Conversely, suppose that $z = \bar{z}$. Then we have

$$\operatorname{Re} z = \frac{1}{2}(z + \bar{z}) = \frac{1}{2}(z + z) = z$$

so z has only a real part, and hence must be a real number. ■

Lemma 1.1.5. *The following are true for all $z, w \in \mathbb{C}$.*

$$(1) \quad \|z + w\|^2 = \|z\|^2 + 2 \operatorname{Re} z\bar{w} + \|w\|^2.$$

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

$$(3) \quad \|z + w\|^2 + \|z - w\|^2 = 2(\|z\|^2 + \|w\|^2).$$

Proof. We first notice that $\|z + w\|^2 = (z + w)\overline{(z + w)} = (z + w)(\bar{z} + \bar{w}) = z\bar{z} + z\bar{w} + w\bar{z} + w\bar{w} = \|z\|^2 + z\bar{w} + w\bar{z} + \|w\|^2$. Now, let $z = a + ib$ and $w = c + id$. Then we have

$$\begin{aligned} (a + ib)(c - id) &= (ac + bd) - i(ad - bc) \\ (c + id)(a - ib) &= (ac + bd) + i(ad - bc) \end{aligned}$$

so that $z\bar{w} + w\bar{z} = 2(ac + bd) = 2 \operatorname{Re} z\bar{w}$, and we are done. To get the identity for $\|z - w\|^2$, we simply replace w by $-w$, and use the above argument.

Now, we have that $\|z + w\|^2 = \|z\|^2 + 2 \operatorname{Re} z\bar{w} + \|w\|^2$, and $\|z - w\|^2 = \|z\|^2 - 2 \operatorname{Re} z\bar{w} + \|w\|^2$, so that adding them together, the terms $2 \operatorname{Re} z\bar{w}$ cancel out and we are left with

$$\|z + w\|^2 + \|z - w\|^2 = 2(\|z\|^2 + \|w\|^2)$$

■

Lemma 1.1.6. *Let $R(z) \in \mathbb{C}(z)$ a rational function in z . Then if R has coefficients in \mathbb{R} , then $\overline{R(z)} = R(\bar{z})$.*

Proof. We first observe the polynomial $f \in \mathbb{C}[z]$, of finite degree $\deg f = n$, and of the form

$$f(z) = a_0 + a_1z + \cdots + a_nz^n$$

Then if f has all coefficients in \mathbb{R} ; i.e. $f \in \mathbb{R}[z]$, where $z \in \mathbb{C}$ is treated as indeterminant, then we have that since each $a_i \in \mathbb{R}$, then $\overline{a_i z^i} = \overline{a_i} z^i = a_i \bar{z}^i$. So that

$$\overline{f(z)} = \overline{(a_0 + a_1z + \cdots + a_nz^n)} = a_0 + a_1\bar{z} + \cdots + a_n\bar{z}^n$$

which makes $\overline{f(z)} = f(\bar{z})$. Now, one can also extend f to a polynomial of infinite degree by taking $n \rightarrow \infty$, and the same holds.

Now, let $R(z) \in \mathbb{C}(z)$ a rational function. Recall that $R(z)$ is of the form

$$R(z) = \frac{f(z)}{g(z)} \text{ with } g \neq 0$$

for some polynomials $f, g \in \mathbb{C}[z]$. Then if R has all real coefficients, so do f and g , and hence we get

$$\overline{R(z)} = \frac{\overline{f(z)}}{\overline{g(z)}} = \frac{f(\bar{z})}{g(\bar{z})} = R(\bar{z})$$

which completes the proof. ■

1.2 The Complex Plane

Definition. We define the **complex plane** to be the space of points (x, y) of \mathbb{R}^2 for which $z = x + iy$.

Lemma 1.2.1. *For every $z, w \in \mathbb{C}$ $\|z + w\| \leq \|z\| + \|w\|$.*

Proof. Observe that $-\|z\| \leq \operatorname{Re} z \leq \|z\|$ for all $z \in \mathbb{C}$, so that $\operatorname{Re} z\bar{w} \leq \|z\bar{w}\| = \|z\|\|w\|$. So we get

$$\|z + w\|^2 = \|z\|^2 + \operatorname{Re} z\bar{w} + \overline{\operatorname{Re} z\bar{w}} \leq \|z\|^2 + \|z\|\|w\| + \overline{\|z\|\|w\|} = (\|z\| + \|w\|)^2$$

Taking square roots gives us the result. ■

Corollary. $\|z + w\| = \|z\| + \|w\|$ if $z = tw$ for some $t \geq 0$.

Corollary. If $z_1, \dots, z_n \in \mathbb{C}$, then $\|z_1 + \dots + z_n\| \leq \|z_1\| + \dots + \|z_n\|$.

Proof. By induction on n . ■

Corollary. For all $z, w \in \mathbb{C}$, $|\|z\| - \|w\|| \leq \|z - w\|$.

Proof. We have that $\|z\| \leq \|z - w\| + \|w\|$, and $\|w\| \leq \|z - w\| + \|z\|$. So we get $\|z\| - \|w\| \leq \|z - w\|$ and $-\|z - w\| \leq \|w\| - \|z\|$, so that $|\|z\| - \|w\|| \leq \|z - w\|$. ■

Definition. We define the **polar form** of a complex number $z \in \mathbb{C}$ to be the polar coordinates (r, θ) where $r = \|z\|$ and θ is the angle between the line segment from 0 to z and the positive real axis. We call r the **modulus** of z , and θ the **argument** of z . We write $\theta = \arg z$.

Lemma 1.2.2. Let $z = r_1 \cos \theta_1 + r_1 i \sin \theta_1$ and $w = r_2 \cos \theta_2 + r_2 i \sin \theta_2$. Then

$$zw = r_1 r_2 \cos(\theta_1 + \theta_2) + r_1 r_2 i \sin(\theta_1 + \theta_2)$$

so that $\arg zw = \arg z + \arg w$.

Proof. We multiply the expanded forms of z and w together and use the trigonometric identities to get the result. ■

Corollary. If $z_k = r_k \cos \theta_k + r_k i \sin \theta_k$, then

$$z_1 \dots z_n = (r_1 \dots r_n) \cos(\theta_1 + \dots + \theta_n) + (r_1 \dots r_n) i \sin(\theta_1 + \dots + \theta_n)$$

Proof. By induction on n . ■

Theorem 1.2.3 (DeMoivre's Theorem). For all integers $n \geq 0$, if $z = \cos \theta + i \sin \theta$, then

$$z^n = \cos n\theta + i \sin n\theta$$

Proof. We use the corollary to lemma 1.2.2 recursively on z^n . ■

Lemma 1.2.4. For each nonzero $a \in \mathbb{C}$, and integer $n \geq 2$, the polynomial $z^n - a$ has roots all z of the form

$$z = \|a\|^{\frac{1}{n}} \left(\cos \frac{\alpha + 2k\pi}{n} + i \sin \frac{\alpha + 2k\pi}{n} \right) \text{ for all } 0 \leq k \leq n-1$$

where $a = \|a\| \cos \alpha + \|a\| i \sin \alpha$

Proof. Let $a = \|a\| \cos \alpha + \|a\| i \sin \alpha$. Then we have $z^n - a = 0$ has as solution

$$z' = \|a\|^{\frac{1}{n}} \left(\cos \frac{\alpha + 2\pi}{n} + i \sin \frac{\alpha + 2\pi}{n} \right)$$

The rest of the solutions are obtained by noting that $(z')^n - a = 0$. ■

Definition. Let $a \in \mathbb{C}$ a nonzero complex number. We call the roots of the polynomial $z^n - a \in \mathbb{C}[z]$ the **n -th roots** of a . We call the roots of $z^n - 1 \in \mathbb{C}[z]$ the **n -th roots of unity**.

Example 1.2. The n -th roots of unity are all complex numbers of the form

$$z = \cos \frac{2k\pi}{n} + i \sin \frac{2k\pi}{n} \text{ for all } 0 \leq k \leq n-1$$

Lemma 1.2.5. Let $L \subseteq \mathbb{C}$ a straight line in \mathbb{C} . Then $L = \{z \in \mathbb{C} : \operatorname{Im} \frac{z-a}{b} = 0\}$, where $z = a + tb$ for some $t \in \mathbb{R}$.

Proof. Let a be any point in L , and b the direction vector of L . Then if $z \in L$ $z = a + tb$ for some $t \in \mathbb{R}$. Since $b \neq 0$, $\operatorname{Im} \frac{z-a}{b} = 0$, since $t = \frac{z-a}{b}$, and $t \in \mathbb{R}$. ■

Corollary. Let $H_a = \{z \in \mathbb{C} : \operatorname{Im} \frac{z-a}{b} > 0\}$ and $K_a = \{z \in \mathbb{C} : \operatorname{Im} \frac{z-a}{b} < 0\}$. Then $H_a = a + H_0$ and $K_a = a - K_0$.

Proof. Suppose that $\|b\| = 1$, and let $a = 0$, then $H_0 = \{z \in \mathbb{C} : \operatorname{Im} \frac{z}{b} > 0\}$. Now, $b = \cos \beta + i \sin \beta$. If $z = r \cos \theta + ri \sin \theta$, then $\frac{z}{b} = r \cos(\theta - \beta) + ri \sin(\theta - \beta)$. So $z \in H_0$ if, and only if $\sin(\theta - \beta) > 0$; that is $\beta < \theta < \pi + \beta$, which makes H_0 the upper half plane about L .

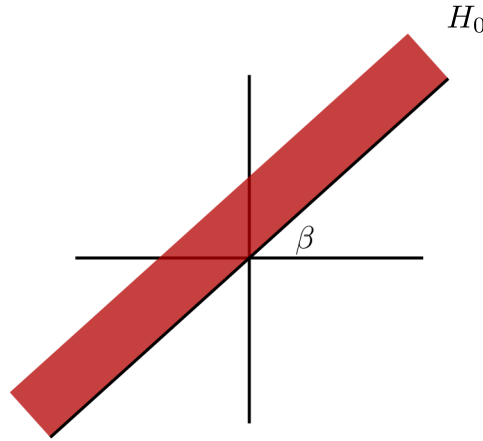


Figure 1.1:

Putting $H_a = \{z \in \mathbb{C} : \operatorname{Im} \frac{z-a}{b} > 0\}$, we get $H_a = a + H_0$. By similar reasoning, we get $K_a = a - K_0$, where $K_a = \{z \in \mathbb{C} : \operatorname{Im} \frac{z-a}{b} < 0\}$. ■

1.3 The Extended Complex Numbers

Definition. We define the **extended complex numbers** to be the set $\mathbb{C}_\infty = \mathbb{C} \cup \{\infty\}$.

Lemma 1.3.1. \mathbb{C}_∞ is homeomorphic to the unit sphere S^2 of \mathbb{R}^3 .

Proof. Identify \mathbb{C} with the plane \mathbb{R}^2 as a subset of \mathbb{R}^3 . Then \mathbb{C} cuts the sphere S^2 along the equator. Now, let $N = (0, 0, 1)$ be the north pole of S^2 . For $z \in \mathbb{C}$, let L_z the line passing through z and N , and hence cuts S^2 at exactly one point $Z \neq N$. If $\|z\| > 1$, Z is in the northern hemisphere of S^2 , and if $\|z\| < 1$, then Z is in the southern hemisphere. If $\|z\| = 1$, then $Z = z$. Then notice that as $\|z\| \rightarrow \infty$, then $Z \rightarrow N$; and so identify N with ∞ in \mathbb{C}_∞ .

Now, let $z = x + iy$ and $Z = (x_1, x_2, x_3)$ a point on S^2 . Then $L_z = \{tN + (1-t)z : t \in \mathbb{R}\}$. Observe then that

$$L_z = \{((1-t)x, (1-t)y, t) : t \in \mathbb{R}\}$$

Then we get

$$1 = (1-t)^2\|z\|^2 + t^2$$

Taking $t \neq 1$ so that $z \neq \infty$

$$Z = \left(\frac{2x}{\|z\|^2 + 1}, \frac{2y}{\|z\|^2 + 1}, \frac{\|z\|^2 - 1}{\|z\|^2 + 1} \right)$$

additionally

$$Z = \left(\frac{z + \bar{z}}{\|z\|^2 + 1}, -i \frac{z - \bar{z}}{\|z\|^2 + 1}, \frac{\|z\|^2 - 1}{\|z\|^2 + 1} \right)$$

Taking $Z \neq N$ and $t = x_1$, we also get by definition of L_z , that

$$z = \frac{x_1 + ix_2}{1 - x_3}$$

Define now, the metric d on \mathbb{C}_∞ by $d(z, w)$ is the distance between the points $Z = (x_1, x_2, x_3)$ and $W = (y_1, y_2, y_3)$ on S^2 . Then we get

$$d(z, w) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + (x_3 - y_3)^2}$$

Squaring both sides we observe that

$$d(z, w)^2 = 2 - 2(x_1y_1 + x_2y_2 + x_3y_3)$$

Using the previous derivations of the components of Z , we finally obtain

$$d(z, w) = \frac{\|z - w\|}{\sqrt{(\|z\|^2 + 1)(\|w\|^2 + 1)}} \text{ for all } z, w \in \mathbb{C}$$

When $w = \infty$, we have

$$d(z, \infty) = \frac{1}{\sqrt{\|z\|^2 + 1}}$$

Then d is the required homeomorphism. ■

Definition. We call the correspondence between S^2 and \mathbb{C}_∞ the **stereographic projection** of S^2 onto \mathbb{C}_∞ .

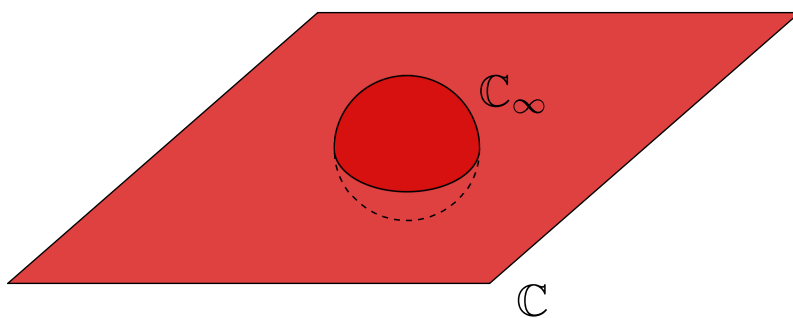


Figure 1.2: The Extended Complex Numbers.

Chapter 2

The Topology of \mathbb{C} .

2.1 Metric Spaces

Definition. A **metric space** is a set X together with a map $d : X \times X \rightarrow \mathbb{R}$ such that for all $x, y, z \in X$

- (1) $d(x, y) \geq 0$ and $d(x, y) = 0$ if, and only if $x = y$.
- (2) $d(x, y) = d(y, x)$.
- (3) $d(x, y) \leq d(x, z) + d(z, y)$ (The Triangle Inequality).

We call d a **metric** on X . If $x \in X$, and $r > 0$, we define the **open ball** centered about x of **radius** r to be the set $B(x, r) = \{y \in X : d(x, y) < r\}$. We define the **closed ball** centered about x of radius r to be the set $\bar{B}(x, r) = \{y \in X : d(x, y) \leq r\}$.

Example 2.1. (1) The metric $d(x, y) = \|z - w\|$ makes \mathbb{R} and \mathbb{C} into metric spaces. In fact, d defines the norm on \mathbb{C} , i.e. $\|z\| = d(z, 0)$.

- (2) If X is a metric space with metric d , and $Y \subset X$, then d makes Y into a metric space.
- (3) Define $d(x + iy, a + ib) = \|x - a\| + \|y - b\|$. Then (\mathbb{C}, d) is a metric space. We call d the **taxicab metric**.
- (4) Define $d(x + iy, a + ib) = \max\{\|x - a\|, \|y - b\|\}$. Then (\mathbb{C}, d) is a metric space. We call d the **square metric**.
- (5) Let X be any set, and define $d : X \times X \rightarrow \mathbb{R}$ by

$$d(x, y) = \begin{cases} 1, & \text{if } x \neq y \\ 0, & \text{if } x = y \end{cases}$$

Then d is a metric on X . Notice also that for any $\varepsilon > 0$, that $B(x, \varepsilon) = \{x\}$ if $\varepsilon \leq 1$, and $B(x, \varepsilon) = X$ if $\varepsilon > 1$.

(6) Define d on \mathbb{R}^n by

$$d(x, y) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2}$$

Then d is a metric on \mathbb{R}^n defining the general norm. That is $\|x\| = d(x, 0)$.

(7) Let S and let $B(S)$ the set of all complex valued functions $f : S \rightarrow \mathbb{C}$ such that $\|f\|_\infty = \sup \{\|f(s)\| : s \in S\}$ is finite. That is, $B(S)$ is the set of all complex valued functions whose image is contained within a disk of finite radius. Define d on $B(S)$ by $d(f, g) = \|f - g\|_\infty$. Let $f, g, h \in B(S)$. Then

$$\|f(s) - g(s)\| = \|(f(s) - h(s)) - (h(s) - g(s))\| \leq \|f(s) - h(s)\| + \|h(s) - g(s)\|$$

taking least upper bounds, we get

$$\|f - g\|_\infty \leq \|f - h\|_\infty + \|h - g\|_\infty$$

Definition. Let X be a metric space together with metric d . We call a subset U of X **open** if there exists an $\varepsilon > 0$ for which $B(x, \varepsilon) \subseteq U$ for every $x \in U$.

Example 2.2. $U = \{z \in \mathbb{C} : a < \operatorname{Re} z < b\}$ is open in \mathbb{C} , but $U = \{z \in \mathbb{C} : \operatorname{Re} z < 0\}$ is not, as $B(0, \varepsilon) \not\subseteq U$ no matter how small we make ε .

Theorem 2.1.1. Let X be a metric space with metric d . Then X is a topological space whose open sets are those subsets of X containing ε -balls for every element, and for $\varepsilon > 0$.

Definition. We call a subset V of a metric space (X, d) **closed** if $X \setminus V$ is open in X .

Lemma 2.1.2. If (X, d) is a metric space, then it is a topology by closed sets.

Definition. Let $A \subseteq X$ where X is a metric space. We define the **interior** of A to be the union of all open sets contained in A , and write $\operatorname{int} A$. We define the **closure** of A to be the intersection of all closed sets containing A and write $\operatorname{cl} A$. We define the **boundary** of A to be $\partial A = \operatorname{cl} A \cap \operatorname{cl} (X \setminus A)$.

Example 2.3. We have $\operatorname{int} \mathbb{Q}(i) = \emptyset$ and $\operatorname{cl} \mathbb{Q}(i) = \mathbb{C}$.

Lemma 2.1.3. Let X be a metric space and $A, B \subseteq X$. Then the following are true

- (1) A is open if, and only if $A = \operatorname{int} A$.
- (2) A is closed if, and only if $A = \operatorname{cl} A$.
- (3) $\operatorname{int} A = X \setminus \operatorname{cl} (X \setminus A)$, $\operatorname{cl} A = X \setminus \operatorname{int} (X \setminus A)$, and $\partial A = \operatorname{cl} A \setminus \operatorname{int} A$.
- (4) $\operatorname{cl} (A \cup B) = \operatorname{cl} A \cup \operatorname{cl} B$.
- (5) $x_0 \in \operatorname{int} A$ if, and only if there is an $\varepsilon > 0$ for which $B(x_0, \varepsilon) \subseteq A$.
- (6) $x_0 \in \operatorname{cl} A$ if, and only if for every $\varepsilon > 0$, $B(x_0, \varepsilon) \cap A \neq \emptyset$.

Definition. A subset A of a metric space X is **dense** in X if $\operatorname{cl} A = X$.

Example 2.4. \mathbb{Q} is dense in \mathbb{R} , notice that $\operatorname{cl} \mathbb{Q} = \mathbb{R}$. Moreover, $\mathbb{Q}(i)$ is dense in \mathbb{C} .

2.2 Connectedness in \mathbb{C}

Definition. We say a metric space X is connected provided there are no disjoint nonempty open sets $A, B \subseteq X$ for which $X = A \cup B$.

Lemma 2.2.1. *A metric space X is connected if its only closed and open sets are the emptyset and itself.*

Example 2.5. Consider the space $X = \{z \in \mathbb{C} : \|z\| < 1\} \cup \{z \in \mathbb{C} : \|z - 3\| < 1\}$. Let $A = \{z \in \mathbb{C} : \|z\| < 1\}$ and $B = \{z \in \mathbb{C} : \|z - 3\| < 1\}$. Then both A and B are open in X . Moreover, A is also closed in X as $B = X \setminus A$. So X is not connected.

Lemma 2.2.2. *A space $X \subseteq \mathbb{C}$ is connected if, and only if it is an interval.*

Proof. Suppose that $X = [a, b]$, where $a, b \in \mathbb{R}$ and $a < b$. Let $A \subseteq X$ be open, with $a \in A$ and $b \in B$ and where $X \neq A$. Then there is an $\varepsilon > 0$ for which $[a, a + \varepsilon) \subseteq A$. Let $r = \sup \{\varepsilon : [a, a + \varepsilon) \subseteq A\}$. If $a \leq x < a + r$, putting $h = a + (r - x) > 0$ there is an $\varepsilon > 0$ for which $r - h < \varepsilon < r$ and $[a, a + \varepsilon) \subseteq A$. However, $a \leq a + (r - h) < a + \varepsilon$ putting $x \in A$. So that $[a, a + r) \subseteq A$. Now, if $a + r \in A$, then by the openness of A , there is a $\delta > 0$ with $[a + r, a + r + \delta) \subseteq A$, which puts $[a + r, a + r + \delta) \subseteq A$. But that contradicts that r is a least upper bound; so $a + r \notin A$.

Now, if A were closed, then $a + r \in B = X \setminus A$, which is open, so that there is a $\delta > 0$ such that $(a + r - \delta, a + r) \subseteq B$, which contradicts that $[a, a + r) \subseteq A$. ■

Remark. Note that the first part of this proof lacks the proof for the other types of intervals.

Definition. Let $z, w \in \mathbb{C}$. We define the **straight line segment** $[z, w]$ from z to w to be the set

$$[z, w] = \{tw + (1 - t)z : 0 \leq t \leq 1\}$$

A **polygon** from z to w is defined to be the set

$$P[z, w] = \bigcup_{k=1}^n [z_k, w_k]$$

where $z_1 = z$, $w_n = w$, and $z_{k+1} = w_k$ for all $1 \leq k \leq n - 1$. When the endpoints of the polygon are understood, we may simply just write P , or we enumerate the points of P as $P = [z, z_2, \dots, z_n, w]$.

Theorem 2.2.3. *An open set U of \mathbb{C} is connected if, and only if for all $z, w \in U$, there exists a polygon $P[z, w]$ from z to w contained in U .*

Proof. Let $P[z, w] \subseteq U$ be the given polygon. Suppose that U were not connected. Then there exist disjoint nonempty open sets Z and W of U (as a subspace of \mathbb{C}) for which $U = Z \cup W$. Let $z \in Z$ and $w \in W$. Consider the case for when $P[z, w] = [z, w]$. Define $S = \{s \in [0, 1] : sw + (1 - s)z \in A\}$ and $T = \{s \in [0, 1] : sw + (1 - s)z \in B\}$. Then notice that S and T are disjoint, and that $S \cup T = [0, 1]$. Moreover, they are open subsets of the interval $[0, 1] \subseteq \mathbb{R}$; but $[0, 1]$ is connected in \mathbb{R} , which is a contradiction. Therefore U must be connected.

On the otherhand, let $w \in Z$ and let $P = [z, z_2, \dots, z_n, w] \subseteq U$. Since U is open, there is an $\varepsilon > 0$ such that $B(w, \varepsilon) \subseteq U$. Now, if $u \in B(w, \varepsilon)$, then $[w, u] \subseteq B(w, \varepsilon) \subseteq U$, so the polygon $Q = P \cup [w, u] \subseteq U$. Hence $B(w, \varepsilon) \subseteq Z$, which makes Z open. On the otherhand, consider $u \in U \setminus Z$, and let $\varepsilon > 0$ such that $B(u, \varepsilon) \subseteq U$. Then there is a $w \in Z \cap B(u, \varepsilon)$. Construct, then a polygon $P[z, u]$ so that $B(u, \varepsilon) \cap Z$ is empty. That is, $B(u, \varepsilon) \subseteq U \setminus Z$ making $U \setminus Z$ open, and hence Z closed. ■

Corollary. *If $U \subseteq \mathbb{C}$ is an open and connected set, then for all $z, w \in U$, there is a polygon $P[z, w]$ in U made up of straight line segments parallel to either the real axis, or the imaginary axis.*

Definition. Let X be a metric space. We call a subset $C \subset X$ a **connected component** if it is maximally connected in X .

Example 2.6. (1) A and B in example 2.5 are connected components.

(2) Let $X = \{\frac{1}{k} : k \in \mathbb{Z}^+\} \cup \{0\}$. Then every connected component is a point of x , and vice versa; with, the exception of 0.

Lemma 2.2.4. *Let X be a metric space with $x_0 \in X$. If $\{D_j\}$ is a collection of connected subsets of X , such that $x_0 \in D_j$, then the union $D = \bigcup D_j$ is connected.*

Proof. Let $A \subseteq D$, which is a metric space, for which A is both open and closed, and nonempty. Then $A \cap D_j$ is open and closed for all j . Now, since D_j is connected, either $A \cap D_j = \emptyset$, or $A \cap D_j = D_j$. Since A is nonempty, we must have the latter case. Then there exists at least one index k for which $A \cap D_k = D_k$. Then if $x_0 \in A$, $x_0 \in A \cap D_k$ so that $x_0 \in D_k$ making $A \cap D_j = D_j$ for all j or $D_j \subseteq A$. In either case, we get $D = A$. ■

Theorem 2.2.5. *The connected components of a metric space partition the space.*

Proof. Let \mathcal{D} the collection of all connected subsets of X containing a point $x_0 \in X$. Then \mathcal{D} is nonempty by definition, and by hypothesis, we have that $C = \bigcup D_j$ is connected, and that $x_0 \in C$.

Now, suppose that $C \subseteq D$ for some connected set D . Then $x_0 \in D$ so that $D \in \mathcal{D}$, and hence $D \subseteq C$. This makes $C = D$, and hence C is a connected component of X . This then implies that $X = \bigcup C_j$ where $\{C_j\}$ is the collection of connected components of X .

Now, consider $\{C_j\}$, and suppose that for distinct components C_1 and C_2 , that there is an $x_0 \in C_1 \cap C_2$. Then $x_0 \in C_1$, and $x_0 \in C_2$ so that $C_1 = C_1 \cup C_2 = C_2$, which is a contradiction. Therefore the connected components are pairwise disjoint. ■

Lemma 2.2.6. *If X is a connected metric space with $A \subseteq X$, and $A \subseteq B \subseteq \text{cl } A$, then B is also connected.*

Corollary. *Connected components of a metric space are closed.*

Theorem 2.2.7. *If U is open in \mathbb{C} , then U has countably many connected components; each of which is open.*

Proof. Let $C \subseteq U$ a connected component, with $x_0 \in C$. Since U is open, there is an $\varepsilon > 0$ for which $B(x_0, \varepsilon) \subseteq U$. Then $B(x_0, \varepsilon) \cup C$ is connected so that $B(x_0, \varepsilon) \cup C = C$, so that $B(x_0, \varepsilon) \subseteq C$. This makes each C open.

Now, let $S = \{a + ib \in \mathbb{Q}(i) : a + ib \in U\}$. Then S is countable by the density of $\mathbb{Q}(i)$ in \mathbb{C} , and each connected component of U contains a point of S . This implies there are countably many such components. ■

2.3 Completeness in \mathbb{C}

Definition. We say a sequence $\{x_n\}$ of points of a metric space X **converges** to a point $x \in X$ if for every $\varepsilon > 0$, there is an $N \in \mathbb{Z}^+$ for which

$$d(x, x_n) < \varepsilon \text{ whenever } n \geq N$$

If $\{x_n\}$ converges to x , we write $\{x_n\} \rightarrow x$, or $\lim x_n = x$.

Lemma 2.3.1. *Let X be a metric space. A set $V \subseteq X$ is closed if, and only if for every sequence $\{x_n\}$ of points in V , $\{x_n\}$ converges to a point $x \in V$.*

Proof. If V is closed, and $\{x_n\} \rightarrow x$, then for every $\varepsilon > 0$ and $x_n \in B(x, \varepsilon)$, we get that $B(x, \varepsilon) \cap V \neq \emptyset$ so that $x \in \text{cl } V = V$.

Conversely, suppose that V is not closed. Then there exists a point $x_0 \in \text{cl } V \setminus V$. Then we get that for every $\varepsilon > 0$, the set $B(x_0, \varepsilon) \cap V \neq \emptyset$ so that for all $n \in \mathbb{Z}^+$, there is an $x_n \in B(x_0, \frac{1}{n}) \cap V$. This makes $d(x_0, x_n) < \frac{1}{n}$, so that $\{x_n\} \rightarrow x_0$. Since $x_0 \notin V$, the condition fails. ■

Definition. We call a point $x \in X$ of a metric space X a **limit point** of a subset $A \subseteq X$ if there exists a sequence of points $\{x_n\}$ in A such that $\{x_n\} \rightarrow x$.

Example 2.7. Consider \mathbb{C} and let $A = [0, 1] \cup \{i\}$. Then each point of $[0, 1]$ is a limit point of A , but i is not a limit point of A .

Lemma 2.3.2. *A subset of a metric space is closed if, and only if it contains all its limit points. Moreover, if A is a subset of a metric space X , then $\text{cl } A = A \cup A'$, where A' is the collection of all limit points of A .*

Definition. We call a sequence $\{x_n\}$ of points of a metric space **Cauchy** if for every $\varepsilon > 0$ there is an $N \in \mathbb{Z}^+$ for which

$$d(x_m, x_n) < \varepsilon \text{ for all } m, n \geq N$$

If X is a metric space in which every Cauchy sequence converges to a point in X , then we say X is **complete**.

Theorem 2.3.3. *The field \mathbb{C} of complex numbers is complete.*

Proof. Let $\{z_n\}$ a Cauchy sequence of complex numbers with $z_n = x_n + iy_n$. Then the sequences $\{x_n\}$ and $\{y_n\}$ are Cauchy in \mathbb{R} . Since \mathbb{R} is a complete metric space, we observe that there exist $x, y \in \mathbb{R}$ for which $\{x_n\} \rightarrow x$ and $\{y_n\} \rightarrow y$. This makes $\{z_n\} \rightarrow z$ with $z = x + iy \in \mathbb{C}$. ■

Definition. Let X be a metric space and $A \subseteq X$. We define the **diameter** of A to be the least upper bound:

$$\text{diam } A = \sup \{d(x, y) : x, y \in A\}$$

of all distances of points in A .

Theorem 2.3.4 (Cantor's theorem). *A metric space X is complete if, and only if for every decreasing sequence $\{F_n\}$ of nonempty closed sets, with $\text{diam } F_n \rightarrow 0$ for all n , then the intersection*

$$F = \bigcap F_n$$

consists of a single point.

Proof. Suppose that X is complete. Let $\{F_n\}$ a sequence of closed sets such that

- (1) $F_{n+1} \subseteq F_n$; i.e. $\{F_n\}$ is a decreasing sequence.
- (2) $\lim \text{diam } F_n \rightarrow 0$.

Let $x_n \in F_n$. If $n, m \geq N$ then $x_m, x_n \in F_N$ so that $d(x_m, x_n) \leq \text{diam } F_N$ by definition. By hypothesis, choose an N large enough such that $\text{diam } F_N < \varepsilon$ for some $\varepsilon > 0$. This makes the sequence $\{x_n\}$ Cauchy. Then by the completeness of X $\{x_n\} \rightarrow x$ for some $x \in X$. Since $x_n \in F_n$ for all $n \geq N$, we get that $F_n \subseteq F_N$ and hence $x \in F_N$ which puts

$$x \in F = \bigcap F_n$$

Now, if $y \in F$, then $x, y \in F_n$ for all n which gives $d(x, y) \leq \text{diam } F_n \rightarrow 0$. So $d(x, y) = 0$ which makes $x = y$ and so $F = \{x\}$.

Conversely, let $\{x_n\}$ be Cauchy in X , and take $F_n = \text{cl } \{x_n, x_{n+1}, \dots\}$. Then $F_{n+1} \subseteq F_n$, making $\{F_n\}$ decreasing sequence. If $\varepsilon > 0$, choose an $N > 0$ such that $d(x_m, x_n) < \varepsilon$ for any $m, n \geq N$. Then $\text{diam } F_n \leq \varepsilon$. By hypothesis, there is an $x_0 \in X$ such that $F = \bigcap F_n = \{x_0\}$. Moreover, $x_0 \in F_n$ so that $d(x_0, x_m) \leq \text{diam } F_n \rightarrow 0$, which puts $\{x_n\} \rightarrow x \in X$ which makes X complete. ■

Lemma 2.3.5. *If X is a complete metric space, and $Y \subseteq X$, then Y is complete if, and only if Y is closed in X .*

Proof. Suppose that Y is complete and let y a limit point of Y . Then there exists a sequence $\{y_n\}$ of points of Y for which $\{y_n\} \rightarrow y$. This makes $\{y_n\}$ Cauchy, and so $\{y_n\} \rightarrow x_0 \in Y$. It follows that $y = x_0$, so that $Y' \subseteq Y$ and hence Y is closed. ■

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