

Math 234A: Homework 1

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Problem 1

(i) **(Parallelogram identity)** Let $z, w \in \mathbb{C}$. Show that

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

Proof. Let $z, w \in \mathbb{C}$ with $z = x + iy$ and $w = u + iv$ with $x, y \in \mathbb{R}$ and $u, v \in \mathbb{R}$. Our goal is to show that

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

Consider $|z - w|^2$ and notice that

$$z - w = (x - u) + i(y - v).$$

By definition of the modulus, we have

$$\begin{aligned} |z - w|^2 &= (z - w)\overline{z - w} \\ &= ((x - u) + i(y - v))((x - u) - i(y - v)) \\ &= (x - u)^2 + (y - v)^2 \\ &= x^2 - 2xu + u^2 + y^2 - 2yv + v^2 \\ &= (x^2 + y^2) - 2(xu + yv) + (u^2 + v^2) \\ &= |z|^2 - 2(xu + yv) + |w|^2. \end{aligned}$$

Note that

$$z + w = (x + u) + i(y + v).$$

$$\begin{aligned} |z + w|^2 &= (z + w)\overline{z + w} \\ &= ((x + u) + i(y + v))((x + u) - i(y + v)) \\ &= (x + u)^2 + (y + v)^2 \\ &= x^2 + 2xu + u^2 + y^2 + 2yv + v^2 \\ &= |z|^2 + 2(xu + yv) + |w|^2. \end{aligned}$$

Adding these two moduli together gives us

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

which is our desired result. ■

(ii) **(Binomial Expansion)**: Let $z, w \in \mathbb{C}$ and n be a positive integer. Show that

$$(z + w)^n = \sum_{k=0}^n \binom{n}{k} z^k w^{n-k}$$

where $\binom{n}{k} = \frac{n!}{k!(n-k)!}$.

Proof. Let $z, w \in \mathbb{C}$. We proceed via induction on $n \in \mathbb{Z}^+$ to show that

$$(z + w)^n = \sum_{k=0}^n \binom{n}{k} z^k w^{n-k}$$

where $\binom{n}{k} = \frac{n!}{k!(n-k)!}$. Let $n = 1$ be our base case. Then we have

$$\begin{aligned} \sum_{k=0}^1 \binom{1}{k} z^k w^{1-k} &= \binom{1}{0} z^0 w + \binom{1}{1} z^1 w^0 \\ &= (z + w)^1, \end{aligned}$$

which tells us that the result holds in our base case. Now, suppose the result holds for n th case. We will show the result holds for the $n + 1$ case. By our induction hypothesis, we see that

$$\begin{aligned} (z + w)^{n+1} &= (z + w)(z + w)^n \\ &= (z + w) \sum_{k=0}^n \binom{n}{k} z^k w^{n-k} \\ &= \sum_{k=0}^n \binom{n}{k} z^{k+1} w^{n-k} + w \sum_{k=0}^n \binom{n}{k} z^k w^{n-k+1}. \end{aligned}$$

Reordering indices in the first summation by setting $m = k + 1$, we have

$$\begin{aligned} \sum_{k=0}^n \binom{n}{k} z^{k+1} w^{n-k} + w \sum_{k=0}^n \binom{n}{k} z^k w^{n-k+1} &= \sum_{m=1}^{n+1} \binom{n}{m-1} z^m w^{(n+1)-m} \\ &\quad + \sum_{k=0}^n \binom{n}{k} z^k w^{(n-k)+1}. \end{aligned}$$

Then separating the first and last term of each summation, respectively, we have

$$\begin{aligned} (z + w)^{n+1} &= \binom{n}{n} z^n w + \sum_{m=1}^n \binom{n}{m-1} z^m w^{(n-k)+1} + \sum_{k=1}^n \binom{n}{k} z^k w^{n-k+1} + \binom{n}{0} w^{n+1} \\ &= \binom{n}{n} z^n w + \sum_{k=1}^n \left[\binom{n}{k} + \binom{n}{k-1} \right] z^k w^{(n+1)-k} + \binom{n}{0} w^{n+1}. \end{aligned}$$

Using the fact that

$$\binom{n}{k} + \binom{n}{k-1} = \binom{n+1}{k}$$

and collecting the first and last terms of the summation, we see that

$$\begin{aligned} (z + w)^{n+1} &= \binom{n}{0} z^0 w^{n+1} + \sum_{k=1}^n \binom{n+1}{k} z^k w^{(n+1)-k} + \binom{n}{n} z^{n+1} w^0 \\ &= \sum_{k=0}^{n+1} \binom{n+1}{k} z^k w^{(n+1)-k} \end{aligned}$$

which completes our induction argument. ■

Problem 2

For $z, w \in \mathbb{C}$. Define $\langle z, w \rangle = \Re(z\bar{w})$. (If we think of \mathbb{C} as two dimensional real vector space, then $\langle \cdot, \cdot \rangle$ defines an inner product on \mathbb{C}).

(i) Cauchy Schwarz Inequality: Show that $|\langle z, w \rangle|^2 \leq |z|^2 |w|^2$ for all $z, w \in \mathbb{C}$.

Proof. Let $z, w \in \mathbb{C}$. Using the fact that $|\Re(z\bar{w})| \leq |z|$ and $|z| = |\bar{z}|$, we see that

$$\begin{aligned} |\langle z, w \rangle|^2 &= |\Re(z\bar{w})|^2 \leq |z\bar{w}|^2 \\ &= |z|^2 |\bar{w}|^2 \\ &= |z|^2 |w|^2. \end{aligned}$$

Thus, we conclude that $|\langle z, w \rangle|^2 \leq |z|^2 |w|^2$. ■

(ii) Triangle Inequalities: Show

$$|z \pm w| \leq |z| + |w|$$

and

$$||z| - |w|| \leq |z \pm w|$$

for all $z, w \in \mathbb{C}$.

Proof. Let $z, w \in \mathbb{C}$. We will first show that $|z + w| \leq |z| + |w|$. First, we will show the following results:

$$|z + w|^2 = |z|^2 + 2|\langle z, w \rangle| + |w|^2 \quad (1)$$

and

$$|z - w|^2 = |z|^2 - 2|\langle z, w \rangle| + |w|^2. \quad (2)$$

Let $z = x + iy$ and $w = u + iv$ for $x, y, u, v \in \mathbb{R}$. Observe that

$$z + w = (x + u) + i(y + v)$$

and

$$z - w = (x - u) + i(y - v).$$

Using the definition of the modulus, we see that

$$\begin{aligned} |z + w|^2 &= (z + w)\overline{(z + w)} = ((x + u) + i(y + v))((x + u) - i(y + v)) \\ &= (x + u)^2 + (y + v)^2 \\ &= x^2 + 2xu + u^2 + y^2 + 2yv + v^2 \\ &= (x^2 + y^2) + 2(xu + yv) + (u^2 + v^2) \\ &= |z|^2 + 2\langle z, w \rangle + |w|^2. \quad (\text{since } \langle z, w \rangle = \Re(z\bar{w})) \end{aligned}$$

Similarly, we have

$$\begin{aligned} |z - w|^2 &= (z - w)\overline{(z - w)} = ((x - u) + i(y - v))((x - u) - i(y - v)) \\ &= (x - u)^2 + (y - v)^2 \\ &= x^2 - 2xu + u^2 + y^2 - 2yv + v^2 \\ &= x^2 + y^2 - 2(xu + yv) + u^2 + v^2 \\ &= (x^2 + y^2) - 2\langle z, w \rangle + (u^2 + v^2) \\ &= |z|^2 - 2\langle z, w \rangle + |w|^2. \end{aligned}$$

Now, let us prove that $|z + w| \leq |z| + |w|$. Consider $|z + w|^2$. By part (a), we see that

$$\begin{aligned} |z + w|^2 &= |z|^2 + 2\langle z, w \rangle + |w|^2 \\ &\leq |z|^2 + 2|z||w| + |w|^2 \\ &\leq |z|^2 + 2|z||w| + |w|^2 \\ &= (|z| + |w|)^2. \end{aligned}$$

By taking the square root of both sides, we see that

$$|z + w| \leq |z| + |w|.$$

Using this fact, we can see that

$$|z - w| = |z + (-w)| \leq |z| + |-w| = |z| + |w|.$$

To show the second inequality, consider $|z - w|^2$. Then using part (a) again, we have

$$\begin{aligned} |z - w|^2 &= |z|^2 - 2\langle z, w \rangle + |w|^2 \\ &\geq |z|^2 - 2|z||w| + |w|^2 \\ &= (|z| - |w|)^2. \end{aligned}$$

Thus, we see that

$$|z - w| \geq ||z| - |w||.$$

Using this fact, we can say that

$$|z + w| = |z - (-w)| \geq ||z| - |-w|| = ||z| - |w||.$$

■

Problem 3

(Lagrange Identity) Let $z_1, \dots, z_n, w_1, \dots, w_n \in \mathbb{C}$. Show that

$$\left| \sum_{k=1}^n z_k w_k \right|^2 = \sum_{k=1}^n |z_k|^2 \sum_{k=1}^n |w_k|^2 - \sum_{1 \leq i < j \leq n} |z_i \overline{w_j} - z_j \overline{w_i}|^2.$$

Use this to deduce that

$$\left| \sum_{k=1}^n z_k w_k \right|^2 \leq \sum_{k=1}^n |z_k|^2 \sum_{k=1}^n |w_k|^2.$$

Proof. We will show that

$$\sum_{1 \leq i < j \leq n} |z_i \overline{w_j} - z_j \overline{w_i}|^2 = \sum_{k=1}^n |z_k|^2 \sum_{k=1}^n |w_k|^2 - \left| \sum_{k=1}^n z_k w_k \right|^2.$$

By rearranging terms, we see that

$$\sum_{i=1}^n \sum_{j=1}^n |z_i \overline{w_j} - z_j \overline{w_i}|^2 = 2 \sum_{1 \leq i < j \leq n} |z_i \overline{w_j} - z_j \overline{w_i}|^2. \quad (1)$$

Using the definition of modulus and rearranging terms, we can see that

$$\begin{aligned}
\sum_{i=1}^n \sum_{j=1}^n |z_i \overline{w_j} - z_j \overline{w_i}|^2 &= \sum_{i=1}^n \sum_{j=1}^n (z_i \overline{w_j} - z_j \overline{w_i})(\overline{z_i} w_j - \overline{z_j} w_i) \\
&= \sum_{i=1}^n \sum_{j=1}^n (|z_i|^2 |w_j|^2 + |z_j|^2 |w_i|^2) \\
&\quad - \sum_{i=1}^n \sum_{j=1}^n (z_j \overline{z_i} \overline{w_i} w_j + z_i \overline{z_j} \overline{w_j} w_i) \\
&= 2 \sum_{i=1}^n |z_i|^2 \sum_{j=1}^n |z_j|^2 - 2 \left(\sum_{i=1}^n z_i w_i \right) \left(\sum_{j=1}^n \overline{z_j} \overline{w_j} \right) \\
&= 2 \sum_{i=1}^n |z_i|^2 \sum_{j=1}^n |z_j|^2 - 2 \left| \sum_{i=1}^n z_i w_i \right|^2.
\end{aligned}$$

Now, dividing 2 on both sides with the right side of (1), we get our desired result

$$\sum_{1 \leq i < j \leq n} |z_i \overline{w_j} - z_j \overline{w_i}|^2 = \sum_{i=1}^n |z_i|^2 \sum_{j=1}^n |z_j|^2 - \left| \sum_{i=1}^n z_i w_i \right|^2.$$

Thus, we conclude that

$$\begin{aligned}
\left| \sum_{k=1}^n z_k w_k \right|^2 &= \sum_{k=1}^n |z_k|^2 \sum_{k=1}^n |w_k|^2 - \sum_{1 \leq i < j \leq n} |z_i \overline{w_j} - z_j \overline{w_i}|^2 \\
&\leq \sum_{k=1}^n |z_k|^2 \sum_{k=1}^n |w_k|^2.
\end{aligned}$$

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Problem 4

Express the following complex number in the form $\alpha + i\beta$:

(i) $(1 + i)^{-1}$

Solution. Observe that

$$(1 + i)^{-1} = \frac{1}{1 + i}$$

and that

$$\frac{1}{1 + i} \cdot \frac{(1 - i)}{(1 - i)} = \frac{(1 - i)}{1 - i^2} = \frac{1 - i}{2} = \frac{1}{2} - \frac{1}{2}i.$$

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(ii) $(1 + i)/2i$

Solution. Observe that

$$\frac{(1 + i)}{2i} = \frac{1}{2i}(1 + i) = \frac{1}{2i} + \frac{1}{2} = \frac{1}{2} - \frac{1}{2}i.$$

■

(iii) $(5 + 5i)^{10}$

Solution. Let $z = 1 + i$. Observe that we can write

$$(5 + 5i)^{10} = 5^{10}(1 + i)^{10}.$$

Note that

$$r = \sqrt{1^2 + 1^2} = \sqrt{2}.$$

Furthermore, we have

$$\tan^{-1}(1/1) = \tan^{-1}(1) = \frac{\pi}{4}.$$

Using De Moivre's formula, we can write

$$\begin{aligned} z^{10} &= (\sqrt{2})^{10}(\cos(10\theta) + i\sin(10\theta)) \\ &= (\sqrt{2})^{10}(\cos(5\pi/2) + i\sin(5\pi/2)) \\ &= (\sqrt{2})^{10}i. \end{aligned}$$

Then we have

$$(5 + 5i)^{10} = 5^{10}(\sqrt{2})^{10}i = 312500000i.$$

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(iv) $\left(\frac{2+i}{3-2i}\right)^2$

Solution. Our first step is to get $\frac{2+i}{3-2i}$ in terms of $\alpha + i\beta$. Thus, observe that

$$\frac{2+i}{3-2i} = \frac{2+i}{3-2i} \cdot \frac{3+2i}{3+2i} = \frac{7i+4}{13} = \frac{4}{13} + i\frac{7}{13}.$$

Furthermore, we have

$$\left(\frac{4}{13} + i\frac{7}{13}\right)^2 = \frac{1}{169}(4+7i)^2 = \frac{1}{169}(16+46i-49) = \frac{1}{169}(-33+46i).$$

Thus, we have that

$$\left(\frac{2+i}{3-2i}\right)^2 = \frac{-33}{169} + \frac{46}{169}i$$

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(v) $\left(\frac{-1+i\sqrt{3}}{2}\right)^3.$

Solution. Denote $z = \frac{-1}{2} + i\frac{\sqrt{3}}{2}$. Then observe that

$$\theta = \tan^{-1}\left(\frac{\sqrt{3}/2}{-1/2}\right) = \tan^{-1}(-\sqrt{3}) = \frac{2\pi}{3}.$$

Furthermore, we have

$$r = \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{\sqrt{3}}{2}\right)^2} = 1.$$

Using De Moivre's formula, we have that

$$z^3 = 1^3 \cdot \left(\cos\left(3 \cdot \frac{2\pi}{3}\right) + i\sin\left(3 \cdot \frac{2\pi}{3}\right)\right) = \cos(2\pi) + i\sin(2\pi) = 1 + i0 = 1.$$

■

Problem 5

Let $z \in \mathbb{C}^*$ and $z = \gamma(\cos \varphi + i \sin \varphi)$ where $n \in \mathbb{Z}^+$ and

$$w = \gamma^{1/n} \left[\cos \left(\frac{\varphi + 2\pi k}{n} \right) + i \sin \left(\frac{\varphi + 2\pi k}{n} \right) \right]$$

where $k \in \mathbb{Z}$. Show that $w^n = z$.

Proof. Note that for any $n \in \mathbb{N}$ that

$$z^n = (\cos \varphi + i \sin \varphi)^n = \cos n\varphi + i \sin n\varphi. \quad (1)$$

Additionally, $\cos 2\pi k = 1$ for all $k \in \mathbb{Z}$ and $\sin 2\pi k = 0$ for all $k \in \mathbb{Z}$.

Using (1) and the trigonometric addition formulas, we can see that

$$\begin{aligned} w^n &= \left(\gamma^{1/n} \left[\cos \left(\frac{\varphi + 2\pi k}{n} \right) + i \sin \left(\frac{\varphi + 2\pi k}{n} \right) \right] \right)^n \\ &= (\gamma^{1/n})^n \left[\cos \left(\frac{\varphi + 2\pi k}{n} \right) + i \sin \left(\frac{\varphi + 2\pi k}{n} \right) \right]^n \\ &= \gamma \left[\cos \left(n \cdot \frac{\varphi + 2\pi k}{n} \right) + i \sin \left(n \cdot \frac{\varphi + 2\pi k}{n} \right) \right] \\ &= \gamma (\cos(\varphi + 2\pi k) + i \sin(\varphi + 2\pi k)) \\ &= \gamma [(\cos \varphi \cos 2\pi k - \sin \varphi \sin 2\pi k) + i(\sin \varphi \cos 2\pi k + \cos \varphi \sin 2\pi k)] \\ &= \gamma (\cos \varphi + i \sin \varphi) \\ &= z \end{aligned}$$

which ends our proof. ■

Problem 6

(Computing fourth roots): Find your distinct complex numbers w such that $w^4 = z$ for

(i) $z = i$.

Solution. Note that $z = i = 0 + 1 \cdot i$. We can see that $\varphi = \arg(z) = \frac{\pi}{2}$. For $0 \leq k \leq 3$, we see that the arguments are

$$\frac{\varphi + 2\pi k}{4} = \frac{\pi}{8}, \frac{5\pi}{8}, \frac{9\pi}{8}, \frac{13\pi}{8}.$$

For $k = 0$, we see that

$$\cos \left(\frac{\pi}{8} \right) + i \sin \left(\frac{\pi}{8} \right) = \sqrt{\frac{1 + \sqrt{2}/2}{2}} + i \sqrt{\frac{1 - \sqrt{2}/2}{2}}.$$

For $k = 1$, we see that

$$\begin{aligned} \cos \left(\frac{5\pi}{8} \right) + i \sin \left(\frac{5\pi}{8} \right) &= -\sqrt{\frac{1 + \cos(5\pi/4)}{2}} + i \sqrt{\frac{1 - \cos(5\pi/4)}{2}} \\ &= -\sqrt{\frac{1 - \sqrt{2}/2}{2}} + i \sqrt{\frac{1 + \sqrt{2}/2}{2}}. \end{aligned}$$

For $k = 2$, we see that

$$\begin{aligned}\cos\left(\frac{9\pi}{8}\right) + i\sin\left(\frac{9\pi}{8}\right) &= \cos\left(\frac{1}{2} \cdot \frac{9\pi}{4}\right) + i\sin\left(\frac{1}{2} \cdot \frac{9\pi}{4}\right) \\ &= -\sqrt{\frac{1 + \cos(9\pi/4)}{2}} - i\sqrt{\frac{1 - \cos(9\pi/4)}{2}} \\ &= -\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}}.\end{aligned}$$

Lastly, for $k = 3$, we have

$$\cos\left(\frac{13\pi}{8}\right) + i\sin\left(\frac{13\pi}{8}\right) = \sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}}.$$

Thus, the four solutions are

$$\begin{aligned}k = 0; & \sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}} + i\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}}, \\ k = 1; & -\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}} + i\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}}, \\ k = 2; & -\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}}, \\ k = 3; & \sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}}.\end{aligned}$$

■

(ii) $z = -i$.

Solution. Note that $z = -i = 0 - 1 \cdot i$ and that $\varphi = \arg(z) = \frac{3\pi}{2}$. For $0 \leq k \leq 3$, the arguments are

$$\frac{3\pi}{8}, \frac{7\pi}{8}, \frac{11\pi}{8}, \frac{15\pi}{8}.$$

Let $k = 0$. Then using the result found in problem 5 and the half-angle identity, we have

$$\begin{aligned}\cos\left(\frac{3\pi}{8}\right) + i\sin\left(\frac{3\pi}{8}\right) &= \sqrt{\frac{1 + \cos(3\pi/4)}{2}} - i\sqrt{\frac{1 - \cos(3\pi/4)}{2}} \\ &= \sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}}\end{aligned}$$

Let $k = 1$. We get that

$$\cos\left(\frac{\frac{3\pi}{2} + 2\pi}{4}\right) + i\sin\left(\frac{\frac{3\pi}{2} + 2\pi}{4}\right) = \cos\left(\frac{3\pi}{8} + \frac{\pi}{2}\right) + i\sin\left(\frac{3\pi}{8} + \frac{\pi}{2}\right).$$

Using the sum formula, we see that

$$\begin{aligned}\cos\left(\frac{3\pi}{8} + \frac{\pi}{2}\right) + i\sin\left(\frac{3\pi}{8} + \frac{\pi}{2}\right) &= \left[\cos\left(\frac{3\pi}{8}\right)\cos\left(\frac{\pi}{2}\right) - \sin\left(\frac{3\pi}{8}\right)\sin\left(\frac{\pi}{2}\right)\right] \\ &\quad + i\left[\sin\left(\frac{3\pi}{8}\right)\cos\left(\frac{\pi}{2}\right) + \cos\left(\frac{3\pi}{8}\right)\sin\left(\frac{\pi}{2}\right)\right] \\ &= \sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}} + i\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}}.\end{aligned}$$

For $k = 2$, we employ the same process. Thus, we have

$$\begin{aligned}\cos\left(\frac{3\pi}{8} + \pi\right) + i\sin\left(\frac{3\pi}{8} + \pi\right) &= \left[\cos\left(\frac{3\pi}{8}\right)\cos(\pi) - \sin\left(\frac{3\pi}{8}\right)\sin(\pi)\right] \\ &\quad + i\left[\sin\left(\frac{3\pi}{8}\right)\cos(\pi) + \cos\left(\frac{3\pi}{8}\right)\sin(\pi)\right] \\ &= -\cos\left(\frac{3\pi}{8}\right) - i\sin\left(\frac{3\pi}{8}\right) \\ &= -\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}} + i\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}}.\end{aligned}$$

Lastly, for $k = 3$, we have

$$\begin{aligned}\cos\left(\frac{15\pi}{8}\right) + i\sin\left(\frac{15\pi}{8}\right) &= \cos\left(\frac{3\pi}{8} + \frac{3\pi}{2}\right) + i\sin\left(\frac{3\pi}{8} + \frac{3\pi}{2}\right) \\ &= \left[\cos\left(\frac{3\pi}{8}\right)\cos\left(\frac{3\pi}{2}\right) - \sin\left(\frac{3\pi}{8}\right)\sin\left(\frac{3\pi}{2}\right)\right] \\ &\quad + i\left[\sin\left(\frac{3\pi}{8}\right)\cos\left(\frac{3\pi}{2}\right) + \cos\left(\frac{3\pi}{8}\right)\sin\left(\frac{3\pi}{2}\right)\right] \\ &= \sin\left(\frac{3\pi}{8}\right) - i\cos\left(\frac{3\pi}{8}\right) \\ &= -\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}}.\end{aligned}$$

Hence, the solutions are

$$\begin{aligned}k = 0; & \sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}}, \\ k = 1; & \sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}} + i\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}}, \\ k = 2; & -\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}} + i\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}}, \\ k = 3; & -\sqrt{\frac{1 - \frac{\sqrt{2}}{2}}{2}} - i\sqrt{\frac{1 + \frac{\sqrt{2}}{2}}{2}}.\end{aligned}$$

■

(iii) $z = 1$.

Solution. Note that $z = 1 = 1 + i \cdot 0$. Hence, we have $\varphi = \arg(z) = 0$. For $0 \leq k \leq 3$, we have the arguments

$$0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$$

with each argument corresponding to $k \in [0, 3]$. For $k = 0$, observe that

$$\cos(0) + i \sin(0) = 1.$$

For $k = 1$, we have

$$\cos\left(\frac{\pi}{2}\right) + i \sin\left(\frac{\pi}{2}\right) = 0 + i = i.$$

For $k = 2$, we have

$$\cos \pi + i \sin \pi = -1.$$

Lastly, if $k = 3$ we get

$$\cos\left(\frac{3\pi}{2}\right) + i \sin\left(\frac{3\pi}{2}\right) = -i.$$

Thus, the solutions are

$$\pm 1, \pm i.$$

■

(iv) $z = -1$.

Solution. Let $0 \leq k \leq 3$ and $n = 4$. We will compute all the solution along the interval $0 \leq k \leq 3$. Note that $z = -1 = -1 + i \cdot 0$ and that $\varphi = \arg z = \pi$ and that for $0 \leq k \leq 3$, we have

$$\frac{\varphi + 2\pi k}{4} = \frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \frac{7\pi}{4}.$$

Using the result in problem 5, observe that for $k = 0$, we have

$$\cos\left(\frac{\pi}{4}\right) + i \sin\left(\frac{\pi}{4}\right) = \frac{\sqrt{2}}{2} + i \frac{\sqrt{2}}{2}.$$

Similarly, for $k = 1$, we have

$$\cos\left(\frac{3\pi}{4}\right) + i \sin\left(\frac{3\pi}{4}\right) = -\frac{\sqrt{2}}{2} + i \frac{\sqrt{2}}{2}.$$

For $k = 2$,

$$\cos\left(\frac{5\pi}{4}\right) + i \sin\left(\frac{5\pi}{4}\right) = -\frac{\sqrt{2}}{2} - i \frac{\sqrt{2}}{2}.$$

For $k = 3$, we have

$$\cos\left(\frac{7\pi}{4}\right) + i \sin\left(\frac{7\pi}{4}\right) = \frac{\sqrt{2}}{2} - i \frac{\sqrt{2}}{2}.$$

Thus, we have

$$\begin{aligned} k = 0; & \frac{\sqrt{2}}{2} + i \frac{\sqrt{2}}{2}, \\ k = 1; & -\frac{\sqrt{2}}{2} + i \frac{\sqrt{2}}{2}, \\ k = 2; & -\frac{\sqrt{2}}{2} - i \frac{\sqrt{2}}{2}, \\ k = 3; & \frac{\sqrt{2}}{2} - i \frac{\sqrt{2}}{2}. \end{aligned}$$

■

Problem 7

Sketch the following sets in \mathbb{C} .

(i) $\zeta = \{z \in \mathbb{C} : \Re((1+i)z - 2) = 0\}$.

Solution. Let $z = x + iy$ for $x, y \in \mathbb{R}$. Then we see that

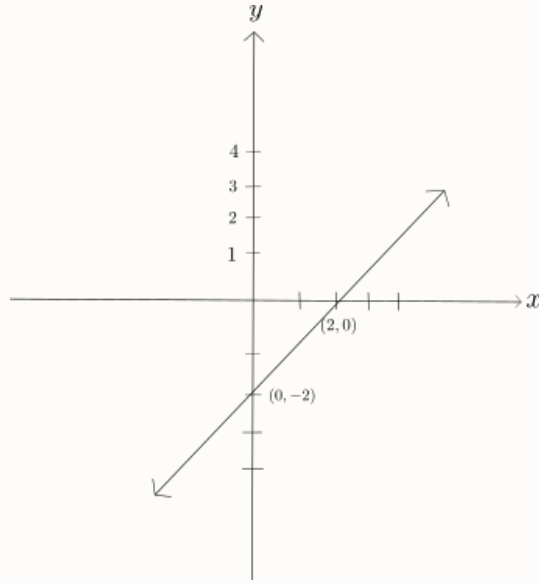
$$\begin{aligned}(1 + i)z - 2 &= (1 + i)(x + iy) - 2 \\ &= (x - y - 2) + i(x + y).\end{aligned}$$

Hence, we have

$$\Re((1 + i)z - 2) = x - y - 2 = 0$$

and so, we have linear equation

$$y = x - 2.$$



(ii) Let $a, c \in \mathbb{R}$ and $b \in \mathbb{C}$ with $\bar{b}b - ac > 0$ and

$$\zeta = \{z \in \mathbb{C} : a|z|^2 + \bar{b}z + b\bar{z} + c = 0\}.$$

Solution. Let $z = x + iy$ and $b = u + iw$ for $x, y, u, w \in \mathbb{R}$. Then observe that

$$\begin{aligned}0 &= a|z|^2 + \bar{b}z + b\bar{z} + c = a(x^2 + y^2) + (u - iw)(x + iy) + c \\ &= ax^2 + ay^2 + 2ux + 2wy + c\end{aligned}$$

which imply that

$$\left[x^2 + \frac{2ux}{a} + \left(\frac{u}{a}\right)^2\right] + \left[y^2 + \frac{2wy}{a} + \left(\frac{w}{a}\right)^2\right] = \frac{u^2 + w^2 - ac}{a}$$

which further implies that

$$\left(x^2 + \frac{u}{a}\right)^2 + \left(y^2 - \frac{w}{a}\right)^2 = \frac{|b|^2 - ac}{a}.$$

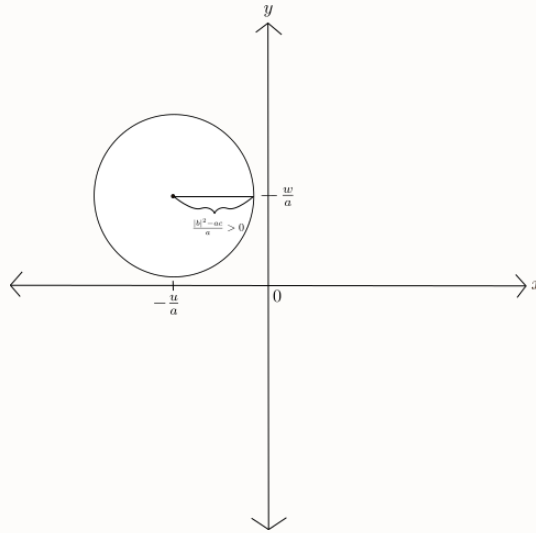
Set

$$\gamma = \frac{|b|^2 - ac}{a}$$

and so

$$\frac{\left(x^2 + \frac{u}{a}\right)^2}{\gamma} + \frac{\left(y^2 - \frac{w}{a}\right)^2}{\gamma} = 1$$

which is an equation of a circle with radius $\gamma > 0$.

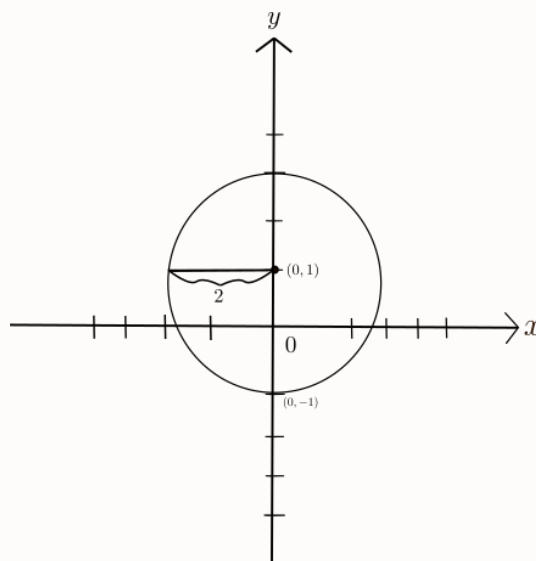


(iii) $\zeta = \{z \in \mathbb{C} : |z - i| = 2\}$.

Proof. Let $z = x + iy$ for $x, y \in \mathbb{R}$. Then we see that

$$\begin{aligned} |z - i|^2 = 4 &\Rightarrow (z - i)\overline{(z - i)} = 4 \\ &\Rightarrow (x + i(y - 1))(x - i(y - 1)) = 4 \\ &\Rightarrow x^2 + (y - 1)^2 = 4 \\ &\Rightarrow \frac{x^2}{4} + \frac{(y - 1)^2}{4} = 1 \end{aligned}$$

which is an equation for a circle in \mathbb{R}^2 . Thus, we have



Problem 8

Let $z, a \in \mathbb{C}$.

- (i) Show that $|1 - z\bar{a}|^2 - |z - a|^2 = (1 - |z|)^2(1 - |a|^2)$.

Proof. Note that $|a|^2 = |\bar{a}|^2$ and that

$$\langle z, a \rangle = \Re(z\bar{a}) = xu + yv = \Re(\bar{z}a) = \langle 1, z\bar{a} \rangle.$$

if $z = x + iy$ and $a = u + iv$ for $x, y, u, v \in \mathbb{R}$. Observe that

$$\begin{aligned} |1 - z\bar{a}|^2 - |z - a|^2 &= [1 - 2\langle 1, z\bar{a} \rangle + |z\bar{a}|^2] - [|z|^2 - 2\langle z, a \rangle + |a|^2] \\ &= |z|^2|a|^2 - |z|^2 - |a|^2 - 1 \\ &= (1 - |z|^2)(1 - |a|^2). \end{aligned}$$

Hence, we see that

$$|1 - z\bar{a}|^2 - |z - a|^2 = (1 - |z|^2)(1 - |a|^2).$$

■

- (ii) Assume that $|a| < 1$. Show that

$$|z| < 1 \Leftrightarrow \left| \frac{z - a}{1 - \bar{a}z} \right| < 1 \quad (1)$$

and

$$|z| = 1 \Leftrightarrow \left| \frac{z - a}{1 - \bar{a}z} \right| = 1. \quad (2)$$

Proof. Suppose $|z| < 1$ and $|a| < 1$. We will first show that the forwards direction of (1).

$$\left| \frac{z - a}{1 - \bar{a}z} \right| < 1.$$

It suffices to show that

$$|z - a|^2 < |1 - \bar{a}z|^2.$$

By part (i), we see that

$$|z - a|^2 = |1 - z\bar{a}|^2 - (1 - |z|^2)(1 - |a|^2). \quad (3)$$

Since $|z| < 1$ and $|a| < 1$, we see that

$$1 - |z|^2 > 0 \text{ and } 1 - |a|^2 > 0.$$

Thus, we see that

$$-(1 - |z|^2)(1 - |a|^2) < 0.$$

Therefore, (3) implies that

$$|z - a|^2 < |1 - \bar{a}z|^2$$

which further implies that

$$\left| \frac{z - a}{1 - \bar{a}z} \right| < 1.$$

Now, suppose for the backwards direction that

$$\left| \frac{z - a}{1 - \bar{a}z} \right| < 1.$$

Note that this is equivalent to saying

$$|z - a|^2 < |1 - \bar{a}z|^2$$

By using the fact that

$$|z - a|^2 = |z|^2 - 2\langle z, a \rangle + |a|^2$$

and

$$|1 - \bar{a}z|^2 = 1 - 2\langle 1, \bar{a}z \rangle + |\bar{a}z|^2.$$

Then observe that

$$|z - a|^2 < |1 - \bar{a}z|^2 \Rightarrow |z|^2 - 2\langle z, a \rangle + |a|^2 < 1 - 2\langle 1, \bar{a}z \rangle + |\bar{a}|^2|z|^2.$$

So, we must have

$$\begin{aligned} |z|^2 - 2\langle z, a \rangle + |a|^2 &< 1 - 2\langle 1, \bar{a}z \rangle + |\bar{a}|^2|z|^2 \\ |z|^2 + |a|^2 &< 1 + |a|^2|z|^2 \end{aligned}$$

which imply that

$$\begin{aligned} |z|^2 &< (1 - |a|^2) + |a|^2|z|^2 \Rightarrow |z|^2(1 - |a|^2) < 1 - |a|^2 \\ &\Rightarrow |z|^2 < \frac{1 - |a|^2}{1 - |a|^2} = 1. \end{aligned}$$

Thus, we see that $|z| < 1$. To prove (2), we can replace the inequalities above with an equal sign and the proof will be the same. ■