

HSC Math Extension 2: Complex Numbers Mastery

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1 Introduction

1.1 Project Overview

This booklet compiles high quality complex numbers problems curated specifically for the HSC Mathematics Extension 2 syllabus. Every problem explores fundamental and advanced techniques involving complex numbers—from basic arithmetic and form conversions to De Moivre’s theorem, Argand diagram geometry, polynomial roots, and geometric transformations. Detailed reasoning showcases common techniques such as modulus-argument manipulation, Euler’s formula applications, and geometric interpretations.

1.2 Target Audience

The explanations are crafted for Extension 2 students aiming to deepen their complex number skills. Each solution explicitly states the conversion steps, theorem applications, and geometric reasoning so that high-school learners can follow every transition.

1.3 How to Use This Booklet

- Read the overview and complex numbers primer before attempting the problems.
- Attempt problems in Part 1 without hints; compare against the detailed solutions to understand model reasoning.
- Use the upside-down hints in Part 2 only after making a genuine attempt.
- Revisit problems after a few days and try to re-derive the arguments without notes to reinforce technique.

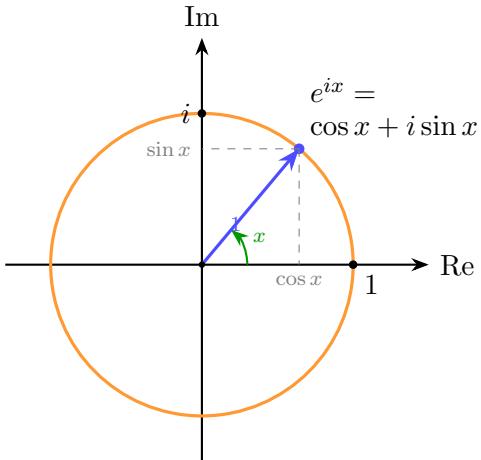
1.4 Complex Numbers Primer

1.4.1 Key Theorems and Formulas

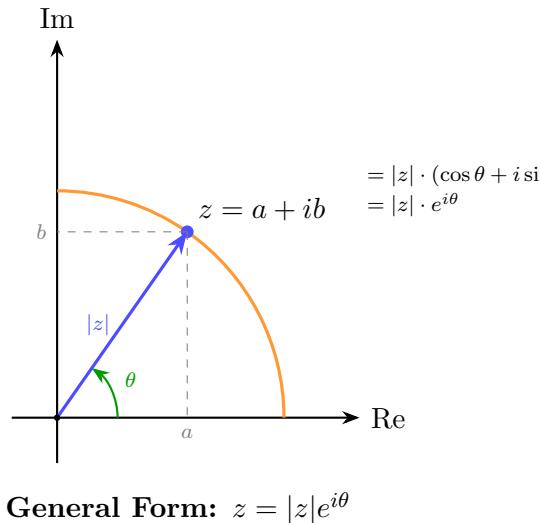
Euler’s Theorem:

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

This connects exponential form with polar form and is fundamental to many proofs.



Unit Circle: e^{ix}



General Form: $z = |z|e^{i\theta}$

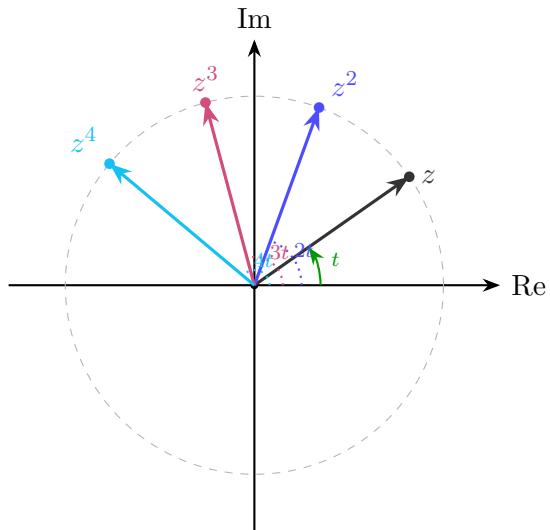
De Moivre's Theorem: For any integer n ,

$$(r(\cos \theta + i \sin \theta))^n = r^n(\cos(n\theta) + i \sin(n\theta))$$

or equivalently, $(re^{i\theta})^n = r^n e^{in\theta}$.

This theorem is invaluable for:

- Finding powers of complex numbers
- Finding n -th roots of complex numbers
- Proving trigonometric identities



For $z = e^{it}$ on unit circle:

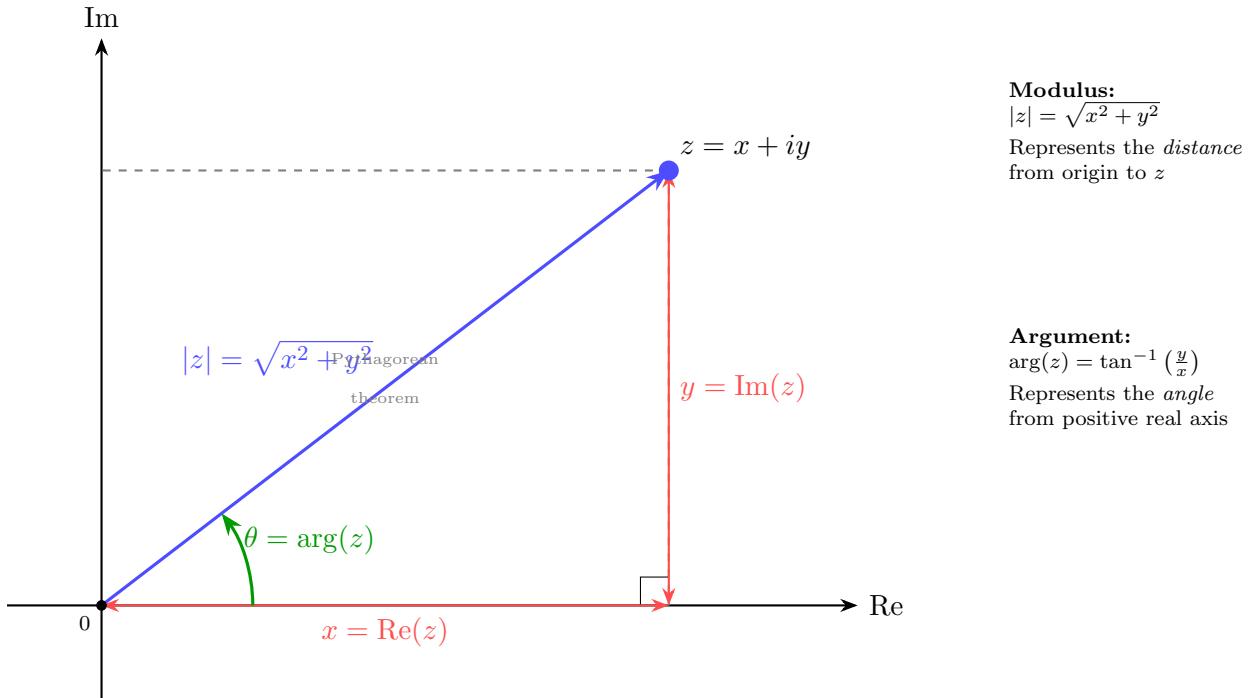
$$\begin{aligned} z^2 &= e^{i(2t)} \text{ rotates by } 2t \\ z^3 &= e^{i(3t)} \text{ rotates by } 3t \\ z^4 &= e^{i(4t)} \text{ rotates by } 4t \end{aligned}$$

Each power multiplies the angle by n .

Powers of z with $|z| = 1$ and $\arg(z) = t$

Modulus and Argument: For $z = x + iy$:

- Modulus: $|z| = \sqrt{x^2 + y^2}$
- Argument: $\arg(z) = \tan^{-1}(y/x)$ (with appropriate quadrant adjustments)
- Properties: $|z_1 z_2| = |z_1||z_2|$, $\arg(z_1 z_2) = \arg(z_1) + \arg(z_2)$ (modulo 2π)



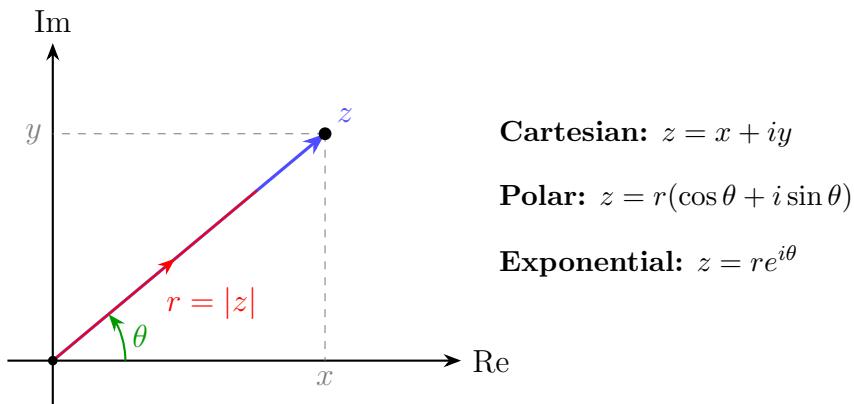
1.4.2 Forms of Complex Numbers

Cartesian Form: $z = x + iy$

Polar Form: $z = r(\cos \theta + i \sin \theta)$ where $r = |z|$ and $\theta = \arg(z)$

Exponential Form: $z = re^{i\theta}$

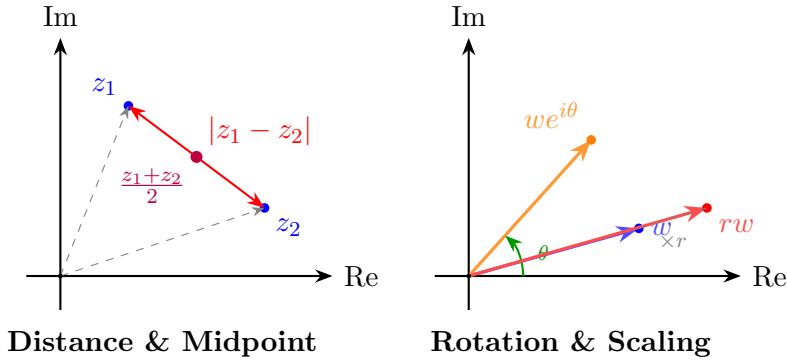
Conversions between these forms are essential skills tested frequently in Extension 2.



1.4.3 Argand Diagram

The Argand diagram visualizes complex numbers as points in the plane, with the real part on the horizontal axis and the imaginary part on the vertical axis. Geometric interpretations include:

- $|z_1 - z_2|$ represents the distance between z_1 and z_2
- $(z_1 + z_2)/2$ represents the midpoint
- Multiplication by $e^{i\theta}$ rotates by angle θ
- Multiplication by r scales by factor r



1.4.4 2D Rotation with Euler's Equation

The multiplication of two complex numbers implies a rotation in 2D space. When we multiply a complex number z by $e^{i\phi}$, it rotates z by angle ϕ while preserving its modulus.

Key Insight: For complex numbers $e^{i\theta}$ and $e^{i\phi}$ on the unit circle:

$$e^{i\theta} \cdot e^{i\phi} = e^{i(\theta+\phi)}$$

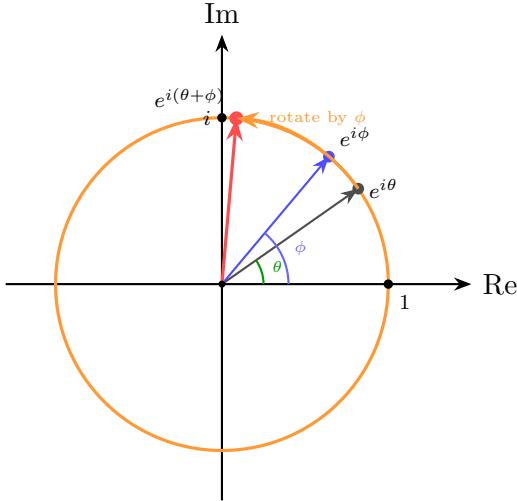
This shows that multiplication adds the angles, which is equivalent to rotation.

General Rotation: To rotate any complex number $z = x + iy = |z|e^{i\theta}$ by angle ϕ :

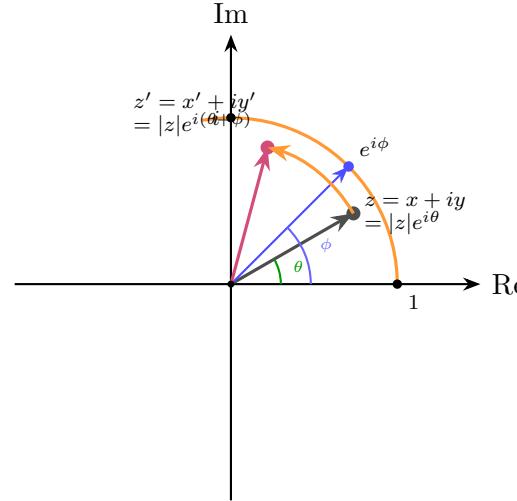
$$\begin{aligned} z' &= z \cdot e^{i\phi} = |z|e^{i\theta} \cdot e^{i\phi} \\ &= |z|e^{i(\theta+\phi)} \\ &= (x + iy)e^{i\phi} \\ &= (x + iy)(\cos \phi + i \sin \phi) \\ &= \cos \phi \cdot x - \sin \phi \cdot y + i(\sin \phi \cdot x + \cos \phi \cdot y) \end{aligned}$$

Matrix Form: This rotation can be expressed as a 2D rotation matrix:

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$



Multiplication implies rotation



2D rotation of complex number

Note: This concept extends to 3D rotations using *quaternions*, which use a rotation axis vector \mathbf{u} instead of a single complex number. The quaternion rotation formula is $\cos \theta + \mathbf{u} \sin \theta$ where \mathbf{u} is the unit vector along the rotation axis.

1.4.5 Notation and Conventions

Throughout this booklet:

- \bar{z} denotes the complex conjugate of z
- $\text{Re}(z)$ and $\text{Im}(z)$ denote the real and imaginary parts
- $\arg(z)$ denotes the principal argument in $(-\pi, \pi]$
- Angles are in radians unless otherwise specified

2 Part 1: Problems and Solutions (Detailed)

Part 1 contains three sets of problems—basic, medium, and advanced. Each set provides five problems. For every problem we present a comprehensive solution without any hints so that learners focus on the full reasoning trail.

2.1 Basic Complex Numbers Problems

Problem 2.1: Basic Complex Arithmetic

Let $z = 5 - i$ and $w = 2 + 3i$. What is the value of $2z + \bar{w}$?

Solution 2.1

First, compute $2z$:

$$2z = 2(5 - i) = 10 - 2i.$$

Next, find the conjugate of w :

$$\overline{w} = \overline{2 + 3i} = 2 - 3i.$$

Now add these results:

$$2z + \overline{w} = (10 - 2i) + (2 - 3i) = 12 - 5i.$$

Therefore, $2z + \overline{w} = 12 - 5i$.

Takeaways 2.1

The conjugate of $a + bi$ is $a - bi$. When adding complex numbers, combine real parts with real parts and imaginary parts with imaginary parts.

Problem 2.2: Finding Square Roots

What value of z satisfies $z^2 = 7 - 24i$?

Solution 2.2

Let $z = a + bi$ where a, b are real. Then:

$$z^2 = (a + bi)^2 = a^2 - b^2 + 2abi = 7 - 24i.$$

Equating real and imaginary parts:

$$\begin{aligned} a^2 - b^2 &= 7 \\ 2ab &= -24. \end{aligned}$$

From the second equation: $ab = -12$, so $b = -\frac{12}{a}$.

Substitute into the first equation:

$$a^2 - \left(-\frac{12}{a}\right)^2 = 7 \implies a^2 - \frac{144}{a^2} = 7.$$

Multiply by a^2 :

$$a^4 - 7a^2 - 144 = 0.$$

Let $u = a^2$:

$$u^2 - 7u - 144 = 0 \implies (u - 16)(u + 9) = 0.$$

Since $u = a^2 \geq 0$, we have $u = 16$, so $a^2 = 16$ giving $a = \pm 4$.

If $a = 4$: $b = -\frac{12}{4} = -3$, so $z = 4 - 3i$.

If $a = -4$: $b = -\frac{12}{-4} = 3$, so $z = -4 + 3i$.

Verify: $(4 - 3i)^2 = 16 - 24i + 9i^2 = 16 - 24i - 9 = 7 - 24i$. ✓

Therefore, $z = 4 - 3i$ or $z = -4 + 3i$.

Takeaways 2.2

To find square roots of complex numbers in Cartesian form, let $z = a + bi$ and equate real and imaginary parts after expanding z^2 . This gives a system of two equations in two unknowns.

Problem 2.3: Complex Roots of Quadratics

Given that $z = 3 + i$ is a root of $z^2 + pz + q = 0$, where p and q are real, what are the values of p and q ?

Solution 2.3

Since the polynomial has real coefficients and $z = 3 + i$ is a root, its complex conjugate $\bar{z} = 3 - i$ must also be a root.

By Vieta's formulas:

$$p = -(z_1 + z_2) = -((3 + i) + (3 - i)) = -6,$$

$$q = z_1 \cdot z_2 = (3 + i)(3 - i) = 9 - i^2 = 9 - (-1) = 10.$$

Therefore, $p = -6$ and $q = 10$.

Takeaways 2.3

For polynomials with real coefficients, complex roots occur in conjugate pairs. Use Vieta's formulas: sum of roots = $-p$ and product of roots = q for $z^2 + pz + q = 0$.

Problem 2.4: Powers of i

Write i^9 in the form $a + ib$ where a and b are real.

Solution 2.4

Note the pattern of powers of i :

$$\begin{aligned} i^1 &= i \\ i^2 &= -1 \\ i^3 &= i^2 \cdot i = -i \\ i^4 &= (i^2)^2 = 1 \\ i^5 &= i^4 \cdot i = i \end{aligned}$$

The pattern repeats every 4 powers. To find i^9 :

$$9 = 4 \cdot 2 + 1,$$

$$\text{so } i^9 = i^{4 \cdot 2 + 1} = (i^4)^2 \cdot i = 1^2 \cdot i = i.$$

Therefore, $i^9 = 0 + 1i$, giving $a = 0$ and $b = 1$.

Takeaways 2.4

Powers of i repeat with period 4: $i^1 = i$, $i^2 = -1$, $i^3 = -i$, $i^4 = 1$. Use division by 4 to find $i^n = i^{n \bmod 4}$.

Problem 2.5: Polar Form Conversion

Write $1 + i$ in the form $r(\cos \theta + i \sin \theta)$.

Solution 2.5

For $z = 1 + i$, first find the modulus:

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

Next, find the argument. Since z is in the first quadrant:

$$\theta = \arg(z) = \tan^{-1}\left(\frac{1}{1}\right) = \tan^{-1}(1) = \frac{\pi}{4}.$$

Therefore:

$$1 + i = \sqrt{2} \left(\cos \frac{\pi}{4} + i \sin \frac{\pi}{4} \right).$$

Takeaways 2.5

To convert $z = x + iy$ to polar form: (1) Find modulus $r = \sqrt{x^2 + y^2}$. (2) Find argument $\theta = \tan^{-1}(y/x)$ (adjust for quadrant). (3) Write $z = r(\cos \theta + i \sin \theta)$.

2.2 Medium Complex Numbers Problems

Problem 2.6: Rhombus on Argand Diagram

On the Argand diagram, the complex numbers 0 , $1 + i\sqrt{3}$, $\sqrt{3} + i$ and z form a rhombus. Find z in the form $a + ib$.

Solution 2.6

In a rhombus, opposite sides are parallel and equal in length. Since we have vertices at 0 , $1 + i\sqrt{3}$, $\sqrt{3} + i$, and z , and they form a rhombus with one vertex at the origin, we need z to be the fourth vertex.

The rhombus has sides:

- From 0 to $1 + i\sqrt{3}$
- From 0 to $\sqrt{3} + i$
- From $1 + i\sqrt{3}$ to z
- From $\sqrt{3} + i$ to z

For a rhombus with one vertex at the origin, if two adjacent vertices are at w_1 and w_2 , then the fourth vertex is at $w_1 + w_2$ (by the parallelogram law).

Therefore:

$$z = (1 + i\sqrt{3}) + (\sqrt{3} + i) = (1 + \sqrt{3}) + i(\sqrt{3} + 1) = (1 + \sqrt{3})(1 + i).$$

Simplifying:

$$z = 1 + \sqrt{3} + i(1 + \sqrt{3}) = (1 + \sqrt{3})(1 + i).$$

Therefore, $z = (1 + \sqrt{3}) + i(1 + \sqrt{3})$.

Takeaways 2.6

In the Argand diagram, a parallelogram (including rhombus) with vertices at 0 , w_1 , w_2 , and z has its fourth vertex at $z = w_1 + w_2$ by the parallelogram law of vector addition.

Problem 2.7: De Moivre's Theorem for Real Results

Given $-\sqrt{3} - i = 2 \left(\cos \left(-\frac{5\pi}{6} \right) + i \sin \left(-\frac{5\pi}{6} \right) \right)$, show that $(-\sqrt{3} - i)^6$ is a real number.

Solution 2.7

Using De Moivre's theorem:

$$\begin{aligned} (-\sqrt{3} - i)^6 &= \left[2 \left(\cos \left(-\frac{5\pi}{6} \right) + i \sin \left(-\frac{5\pi}{6} \right) \right) \right]^6 \\ &= 2^6 \left(\cos \left(6 \cdot \left(-\frac{5\pi}{6} \right) \right) + i \sin \left(6 \cdot \left(-\frac{5\pi}{6} \right) \right) \right) \\ &= 64 (\cos(-5\pi) + i \sin(-5\pi)). \end{aligned}$$

Now evaluate the trigonometric values:

$$\cos(-5\pi) = \cos(5\pi) = \cos(\pi) = -1,$$

$$\sin(-5\pi) = -\sin(5\pi) = -\sin(\pi) = 0.$$

Therefore:

$$(-\sqrt{3} - i)^6 = 64(-1 + 0i) = -64.$$

Since the imaginary part is zero, $(-\sqrt{3} - i)^6 = -64$ is indeed a real number.

Takeaways 2.7

A complex number in polar form $r(\cos \theta + i \sin \theta)$ raised to power n has argument $n\theta$. If $n\theta$ is a multiple of π , then $\sin(n\theta) = 0$ and the result is real.

Problem 2.8: Division in Polar Form

Let $\alpha = 1 + i\sqrt{3}$ and $\beta = 1 + i$. Find the modulus-argument form of $\frac{\alpha}{\beta}$.

Solution 2.8

First, convert α and β to polar form.

For $\alpha = 1 + i\sqrt{3}$:

$$|\alpha| = \sqrt{1^2 + (\sqrt{3})^2} = \sqrt{1+3} = 2,$$

$$\arg(\alpha) = \tan^{-1}\left(\frac{\sqrt{3}}{1}\right) = \frac{\pi}{3}.$$

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

For $\beta = 1 + i$:

$$|\beta| = \sqrt{1^2 + 1^2} = \sqrt{2},$$

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

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

Now compute the quotient:

$$\begin{aligned} \frac{\alpha}{\beta} &= \frac{2}{\sqrt{2}} \left(\cos \left(\frac{\pi}{3} - \frac{\pi}{4} \right) + i \sin \left(\frac{\pi}{3} - \frac{\pi}{4} \right) \right) \\ &= \sqrt{2} \left(\cos \frac{\pi}{12} + i \sin \frac{\pi}{12} \right). \end{aligned}$$

Takeaways 2.8

For division in polar form: $\frac{r_1(\cos \theta_1 + i \sin \theta_1)}{r_2(\cos \theta_2 + i \sin \theta_2)} = \frac{r_1}{r_2} \left(\cos(\theta_1 - \theta_2) + i \sin(\theta_1 - \theta_2) \right)$.

Problem 2.9: Powers and Cartesian Form

Express $(\sqrt{3} - i)^7$ in the form $x + iy$.

Solution 2.9

First, convert $\sqrt{3} - i$ to polar form:

$$r = \sqrt{(\sqrt{3})^2 + (-1)^2} = \sqrt{3+1} = 2,$$

$$\theta = \tan^{-1}\left(\frac{-1}{\sqrt{3}}\right) = -\frac{\pi}{6} \text{ (fourth quadrant).}$$

So $\sqrt{3} - i = 2 \left(\cos\left(-\frac{\pi}{6}\right) + i \sin\left(-\frac{\pi}{6}\right) \right)$.

Apply De Moivre's theorem:

$$\begin{aligned} (\sqrt{3} - i)^7 &= 2^7 \left(\cos\left(7 \cdot \left(-\frac{\pi}{6}\right)\right) + i \sin\left(7 \cdot \left(-\frac{\pi}{6}\right)\right) \right) \\ &= 128 \left(\cos\left(-\frac{7\pi}{6}\right) + i \sin\left(-\frac{7\pi}{6}\right) \right). \end{aligned}$$

Now evaluate:

$$\cos\left(-\frac{7\pi}{6}\right) = \cos\left(\frac{7\pi}{6}\right) = \cos\left(\pi + \frac{\pi}{6}\right) = -\cos\frac{\pi}{6} = -\frac{\sqrt{3}}{2},$$

$$\sin\left(-\frac{7\pi}{6}\right) = -\sin\left(\frac{7\pi}{6}\right) = -\sin\left(\pi + \frac{\pi}{6}\right) = -\left(-\sin\frac{\pi}{6}\right) = \frac{1}{2}.$$

Therefore:

$$(\sqrt{3} - i)^7 = 128 \left(-\frac{\sqrt{3}}{2} + i \cdot \frac{1}{2} \right) = -64\sqrt{3} + 64i.$$

Takeaways 2.9

To compute high powers of complex numbers: (1) Convert to polar form. (2) Apply De Moivre's theorem. (3) Simplify the angle using periodicity and reference angles. (4) Convert back to Cartesian form.

Problem 2.10: Locus as a Curve

The point P on the Argand diagram represents $z = x + iy$ satisfying $z^2 + \bar{z}^2 = 8$. Find the equation of the curve in terms of x and y and state what type of curve it is.

Solution 2.10

Let $z = x + iy$, so $\bar{z} = x - iy$.

Then:

$$z^2 = (x + iy)^2 = x^2 - y^2 + 2ixy,$$

$$\bar{z}^2 = (x - iy)^2 = x^2 - y^2 - 2ixy.$$

Therefore:

$$z^2 + \bar{z}^2 = (x^2 - y^2 + 2ixy) + (x^2 - y^2 - 2ixy) = 2(x^2 - y^2) = 8.$$

Simplifying:

$$x^2 - y^2 = 4.$$

This can be rewritten as:

$$\frac{x^2}{4} - \frac{y^2}{4} = 1,$$

which is a rectangular hyperbola with center at the origin, with branches along the x -axis at $x = \pm 2$.

Takeaways 2.10

To find the locus of points satisfying a complex equation: (1) Substitute $z = x + iy$ and $\bar{z} = x - iy$. (2) Expand and simplify. (3) Equate real and imaginary parts. (4) Identify the curve type.

2.3 Advanced Complex Numbers Problems

Problem 2.11: Geometric Proof with Complex Numbers

Points A and B represent complex numbers z and w on a circle centered at O . Point C represents $z + w$ and also lies on the circle. Show geometrically that $\angle AOB = \frac{2\pi}{3}$.

Solution 2.11

Given that $|z| = |w| = |z + w| = r$ (the radius of the circle), we need to find $\angle AOB$. Since $OACB$ forms a parallelogram (by vector addition), and we know:

- $OA = |z| = r$
- $OB = |w| = r$
- $OC = |z + w| = r$
- $AC = |w| = r$ (opposite side of parallelogram)
- $BC = |z| = r$ (opposite side of parallelogram)

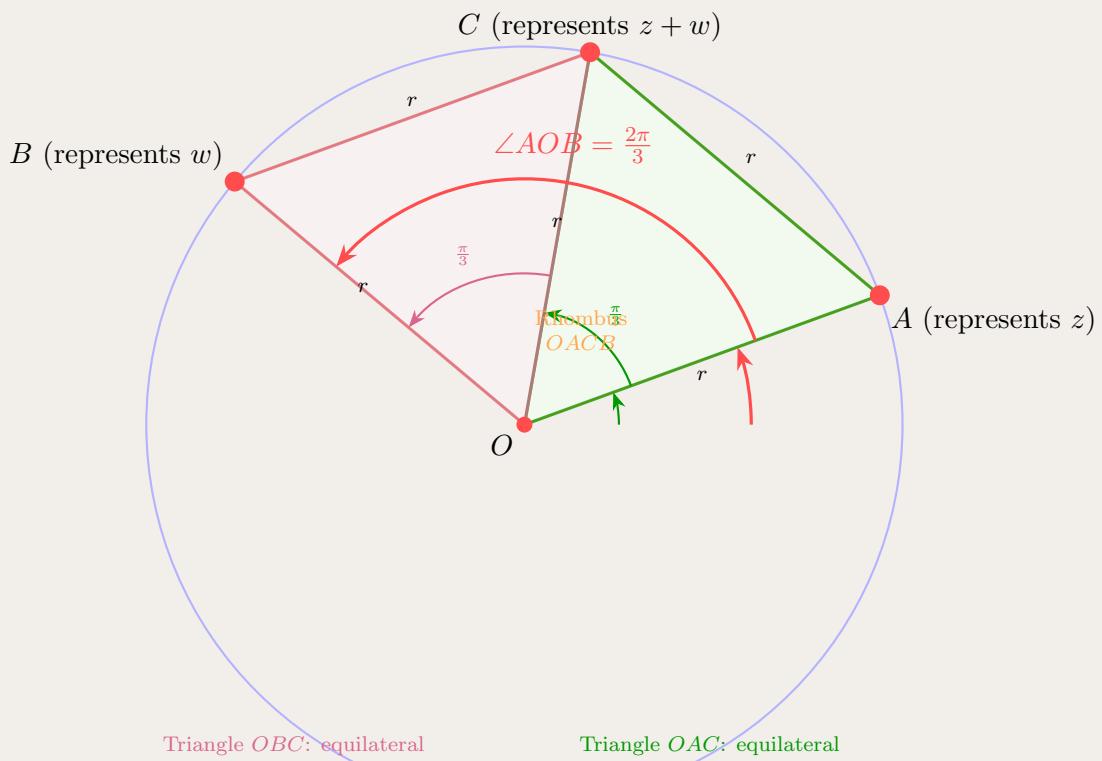
All sides of the rhombus $OACB$ have length r . Moreover, diagonal OC also has length r .

Consider triangle OAC : all three sides have length r (since $OA = AC = OC = r$), so it is equilateral. Therefore, $\angle AOC = \frac{\pi}{3}$.

Similarly, triangle BOC has $OB = BC = OC = r$, so it is also equilateral. Therefore, $\angle BOC = \frac{\pi}{3}$.

Thus:

$$\angle AOB = \angle AOC + \angle BOC = \frac{\pi}{3} + \frac{\pi}{3} = \frac{2\pi}{3}.$$



Takeaways 2.11

When complex numbers are represented geometrically, vector addition corresponds to the parallelogram law. A rhombus with all sides equal to its diagonal consists of two equilateral triangles.

Problem 2.12: Complex Division and Real Parts

Let $z = 2(\cos \theta + i \sin \theta)$. Show that the real part of $\frac{1}{1-z}$ is $\frac{1-2\cos\theta}{5-4\cos\theta}$.

Solution 2.12

First, compute $1 - z$:

$$1 - z = 1 - 2(\cos \theta + i \sin \theta) = (1 - 2 \cos \theta) - 2i \sin \theta.$$

To find $\frac{1}{1-z}$, multiply numerator and denominator by the conjugate of $1 - z$:

$$\begin{aligned} \frac{1}{1-z} &= \frac{1}{(1-2\cos\theta)-2i\sin\theta} \cdot \frac{(1-2\cos\theta)+2i\sin\theta}{(1-2\cos\theta)+2i\sin\theta} \\ &= \frac{(1-2\cos\theta)+2i\sin\theta}{(1-2\cos\theta)^2+(2\sin\theta)^2}. \end{aligned}$$

Compute the denominator:

$$\begin{aligned} (1-2\cos\theta)^2+4\sin^2\theta &= 1-4\cos\theta+4\cos^2\theta+4\sin^2\theta \\ &= 1-4\cos\theta+4(\cos^2\theta+\sin^2\theta) \\ &= 1-4\cos\theta+4 \\ &= 5-4\cos\theta. \end{aligned}$$

Therefore:

$$\frac{1}{1-z} = \frac{(1-2\cos\theta)+2i\sin\theta}{5-4\cos\theta}.$$

The real part is:

$$\operatorname{Re}\left(\frac{1}{1-z}\right) = \frac{1-2\cos\theta}{5-4\cos\theta}.$$

Takeaways 2.12

To find the real part of a complex fraction, rationalize by multiplying by the conjugate of the denominator. Use the identity $\cos^2 \theta + \sin^2 \theta = 1$ to simplify.

Problem 2.13: Finding Complex Roots of Polynomials

Two zeros of $P(x) = x^4 - 12x^3 + 59x^2 - 138x + 130$ are $a + ib$ and $a + 2ib$ where a, b are real and $b > 0$. Find a and b .

Solution 2.13

Since $P(x)$ has real coefficients, complex roots occur in conjugate pairs. If $a + ib$ is a root, then $a - ib$ is also a root. Similarly, if $a + 2ib$ is a root, then $a - 2ib$ is also a root. Therefore, the four roots are: $a + ib, a - ib, a + 2ib, a - 2ib$.

By Vieta's formulas, the sum of roots equals the negative of the coefficient of x^3 divided by the leading coefficient:

$$(a + ib) + (a - ib) + (a + 2ib) + (a - 2ib) = 4a = 12,$$

so $a = 3$.

The product of roots equals the constant term:

$$[(a + ib)(a - ib)][(a + 2ib)(a - 2ib)] = (a^2 + b^2)(a^2 + 4b^2) = 130.$$

Substituting $a = 3$:

$$(9 + b^2)(9 + 4b^2) = 130.$$

Expand:

$$81 + 36b^2 + 9b^2 + 4b^4 = 130,$$

$$4b^4 + 45b^2 + 81 = 130,$$

$$4b^4 + 45b^2 - 49 = 0.$$

Let $u = b^2$:

$$4u^2 + 45u - 49 = 0.$$

Using the quadratic formula:

$$u = \frac{-45 \pm \sqrt{45^2 + 4 \cdot 4 \cdot 49}}{8} = \frac{-45 \pm \sqrt{2025 + 784}}{8} = \frac{-45 \pm \sqrt{2809}}{8} = \frac{-45 \pm 53}{8}.$$

Since $u = b^2 \geq 0$: $u = \frac{-45+53}{8} = \frac{8}{8} = 1$.

Therefore, $b^2 = 1$, so $b = 1$ (since $b > 0$).

Thus, $a = 3$ and $b = 1$.

Takeaways 2.13

For polynomials with real coefficients, complex roots come in conjugate pairs. Use Vieta's formulas (sum and product of roots) along with conjugate pairing to set up equations for unknown parameters.

Problem 2.14: Trigonometric Identity via Complex Numbers

Show that $\cos 4\theta = \cos^4 \theta - 6 \cos^2 \theta \sin^2 \theta + \sin^4 \theta$.

Solution 2.14

By De Moivre's theorem:

$$(\cos \theta + i \sin \theta)^4 = \cos 4\theta + i \sin 4\theta.$$

Expand the left side using the binomial theorem:

$$\begin{aligned} (\cos \theta + i \sin \theta)^4 &= \sum_{k=0}^4 \binom{4}{k} \cos^{4-k} \theta (i \sin \theta)^k \\ &= \cos^4 \theta + 4i \cos^3 \theta \sin \theta + 6i^2 \cos^2 \theta \sin^2 \theta \\ &\quad + 4i^3 \cos \theta \sin^3 \theta + i^4 \sin^4 \theta \\ &= \cos^4 \theta + 4i \cos^3 \theta \sin \theta - 6 \cos^2 \theta \sin^2 \theta \\ &\quad - 4i \cos \theta \sin^3 \theta + \sin^4 \theta \\ &= (\cos^4 \theta - 6 \cos^2 \theta \sin^2 \theta + \sin^4 \theta) \\ &\quad + i(4 \cos^3 \theta \sin \theta - 4 \cos \theta \sin^3 \theta). \end{aligned}$$

Equating real parts:

$$\cos 4\theta = \cos^4 \theta - 6 \cos^2 \theta \sin^2 \theta + \sin^4 \theta.$$

Takeaways 2.14

De Moivre's theorem combined with binomial expansion provides a systematic way to derive multiple-angle formulas. Equate real and imaginary parts to obtain separate identities for $\cos(n\theta)$ and $\sin(n\theta)$.

Problem 2.15: Conjugate Pairs and De Moivre

Show that $(1+i)^n + (1-i)^n = 2(\sqrt{2})^n \cos \frac{n\pi}{4}$.

Solution 2.15

First, convert $1 + i$ and $1 - i$ to polar form.

For $1 + i$:

$$|1 + i| = \sqrt{2}, \quad \arg(1 + i) = \frac{\pi}{4},$$

so $1 + i = \sqrt{2} (\cos \frac{\pi}{4} + i \sin \frac{\pi}{4}) = \sqrt{2} e^{i\pi/4}$.

For $1 - i$:

$$|1 - i| = \sqrt{2}, \quad \arg(1 - i) = -\frac{\pi}{4},$$

so $1 - i = \sqrt{2} (\cos(-\frac{\pi}{4}) + i \sin(-\frac{\pi}{4})) = \sqrt{2} e^{-i\pi/4}$.

By De Moivre's theorem:

$$(1 + i)^n = (\sqrt{2})^n e^{in\pi/4} = (\sqrt{2})^n \left(\cos \frac{n\pi}{4} + i \sin \frac{n\pi}{4} \right),$$
$$(1 - i)^n = (\sqrt{2})^n e^{-in\pi/4} = (\sqrt{2})^n \left(\cos \frac{n\pi}{4} - i \sin \frac{n\pi}{4} \right).$$

Adding:

$$(1 + i)^n + (1 - i)^n = (\sqrt{2})^n \left[\left(\cos \frac{n\pi}{4} + i \sin \frac{n\pi}{4} \right) + \left(\cos \frac{n\pi}{4} - i \sin \frac{n\pi}{4} \right) \right]$$
$$= (\sqrt{2})^n \cdot 2 \cos \frac{n\pi}{4}$$
$$= 2(\sqrt{2})^n \cos \frac{n\pi}{4}.$$

Takeaways 2.15

For conjugate pairs z and \bar{z} in polar form, $z^n + \bar{z}^n = 2|z|^n \cos(n \arg(z))$ because the imaginary parts cancel. This is useful for simplifying sums involving conjugate powers.

3 Part 2: Problems and Solutions (Concise + Hints)

Part 2 revisits three new sets of problems. Solutions are intentionally briefer to encourage student ownership, and every problem includes an upside-down hint.

3.1 Basic Complex Numbers Problems

Problem 3.1: Multiplication by i as Rotation

The complex number z is shown on the Argand diagram. Which of the following best represents iz ?

Hint: Multiplication by i rotates a complex number by 90° counterclockwise about the origin while preserving its modulus.

Solution 3.1: Sketch

If $z = a+bi$, then $iz = i(a+bi) = ai+bi^2 = -b+ai$. This represents a 90° counterclockwise rotation. On the diagram, iz would be at position $(-b, a)$ if z is at (a, b) .

Problem 3.2: Quadrant Determination

The Argand diagram shows z in the first quadrant and w in the second quadrant. Which complex number could lie in the 3rd quadrant: $-w$, $2iz$, \bar{z} , or $w - z$?

Hint: Check the signs of the real and imaginary parts of each option. Third quadrant means both parts are negative.

Solution 3.2: Sketch

If z is in Q1: $\operatorname{Re}(z) > 0, \operatorname{Im}(z) > 0$. If w is in Q2: $\operatorname{Re}(w) < 0, \operatorname{Im}(w) > 0$. Then $w - z$ has $\operatorname{Re}(w - z) = \operatorname{Re}(w) - \operatorname{Re}(z) < 0$ and $\operatorname{Im}(w - z) = \operatorname{Im}(w) - \operatorname{Im}(z)$ which could be negative if $\operatorname{Im}(z) > \operatorname{Im}(w)$. Answer: (D) $w - z$.

Problem 3.3: Doubling the Argument

A complex number z is on the unit circle. Which diagram best shows $\frac{z^2}{|z|}$?

Hint: If $z = e^{i\theta}$, then $z^2 = e^{i2\theta}$ and $|z| = 1$.

Solution 3.3: Sketch

Since $|z| = 1$, we have $\frac{z^2}{|z|} = z^2$. By De Moivre's theorem, z^2 has the same modulus but double the argument. If z is at angle θ , then z^2 is at angle 2θ .

Problem 3.4: Polynomial with Complex Zero

Which polynomial could have $2+i$ as a zero, given that k is real: (A) $x^3 - 4x^2 + kx$, (B) $x^3 - 4x^2 + kx + 5$, (C) $x^3 - 5x^2 + kx$, (D) $x^3 - 5x^2 + kx + 5$?

Hint: If the polynomial has real coefficients and $2+i$ is a root, then $2-i$ must also be a root. The sum of these roots is 4.

Solution 3.4: Sketch

Roots $2+i$ and $2-i$ sum to 4. Let the third root be r . Then sum of all roots = $4+r$. From the coefficient of x^2 : $-(4+r) = -4$ or -5 . If -4 , then $r=0$, giving option (A) or (B). Check: $(x)(x^2 - 4x + 5) = x^3 - 4x^2 + 5x$, but we need +5 constant. Answer: (B).

Problem 3.5: Squaring Complex Numbers

Let $z = 3 + i$ and $w = 2 - 5i$. Find z^2 in the form $x + iy$.

Hint: Use $(a + bi)^2 = a^2 - b^2 + 2abi$.

Solution 3.5: Sketch

$$z^2 = (3 + i)^2 = 9 + 6i + i^2 = 9 + 6i - 1 = 8 + 6i.$$

Problem 3.6: Conjugate Subtraction

Let $z = 4 + i$ and $w = \bar{z}$. Find $w - z$ in the form $x + iy$.

Hint: If $z = 4 + i$, then $\bar{z} = 4 - i$.

Solution 3.6: Sketch

$$w = \bar{z} = 4 - i. \text{ Then } w - z = (4 - i) - (4 + i) = -2i.$$

Problem 3.7: Division by Complex Number

Let $z = 2 + i$. Find $\frac{4}{z}$ in the form $x + iy$.

Hint: Multiply numerator and denominator by $\bar{z} = 2 - i$.

Solution 3.7: Sketch

$$\frac{4}{2+i} = \frac{4(2-i)}{(2+i)(2-i)} = \frac{8-4i}{4-i^2} = \frac{8-4i}{5} = \frac{8}{5} - \frac{4}{5}i.$$

Problem 3.8: Complex Multiplication

Let $z = 3 + i$ and $w = 1 - i$. Find zw in the form $x + iy$.

Hint: Use FOIL: $(a + bi)(c + di) = (ac + bd) + (ad + bc)i$.

Solution 3.8: Sketch

$$zw = (3 + i)(1 - i) = 3 - 3i + i - i^2 = 3 - 2i + 1 = 4 - 2i.$$

Problem 3.9: Another Division

Let $w = 1 - i$. Find $\frac{6}{w}$ in the form $x + iy$.

Hint: Multiply by conjugate: $w = 1 + i$.

Solution 3.9: Sketch

$$\frac{6}{1-i} = \frac{6(1+i)}{(1-i)(1+i)} = \frac{6+6i}{1-i^2} = \frac{6+6i}{2} = 3 + 3i.$$

Problem 3.10: Dividing by Conjugate

Let $z = 4 + i$ and $w = \bar{z}$. Find $\frac{z}{w}$ in the form $x + iy$.

Hint: $w = 4 - i$, so $\frac{z}{w} = \frac{4+i}{4-i}$.

Solution 3.10: Sketch

$$\frac{4+i}{4-i} = \frac{(4+i)(4+i)}{(4-i)(4+i)} = \frac{16+8i+i^2}{16-i^2} = \frac{15+8i}{17} = \frac{15}{17} + \frac{8}{17}i.$$

Problem 3.11: Modulus from Polar Form

Let $z = \frac{1}{2}(\cos \theta + i \sin \theta)$. Find $|z|$.

Hint: For $z = r(\cos \theta + i \sin \theta)$, we have $|z| = r$.

Solution 3.11: Sketch

$$|z| = \frac{1}{2}.$$

Problem 3.12: Division in Cartesian Form

Express $\frac{3-i}{2+i}$ in the form $x + iy$.

Hint: Multiply by $\frac{2-i}{2-i}$.

Solution 3.12: Sketch

$$\frac{3-i}{2+i} = \frac{(3-i)(2-i)}{(2+i)(2-i)} = \frac{6-3i-2i+i^2}{4-i^2} = \frac{5-5i}{5} = 1 - i.$$

Problem 3.13: Addition with Conjugate

Let $z = 1 + 3i$ and $w = 2 - i$. Find $z + \bar{w}$.

Hint: $\bar{w} = 2 - i$.

Solution 3.13: Sketch

$$z + \bar{w} = (1 + 3i) + (2 + i) = 3 + 4i.$$

Problem 3.14: Product with Conjugate

Evaluate $w\bar{z}$ given $w = -1 + 4i$ and $z = 2 - i$.

Hint: $\bar{z} = 2 + i$.

Solution 3.14: Sketch

$$w\bar{z} = (-1 + 4i)(2 + i) = -2 - i + 8i + 4i^2 = -2 + 7i - 4 = -6 + 7i.$$

Problem 3.15: Polar Form of Given Number

Let $w = 1 + i\sqrt{3}$. Express w in modulus-argument form.

Hint: $|w| = \sqrt{1 + 3} = 2$, and $\arg(w) = \tan^{-1}(3/1) = \pi/3$.

Solution 3.15: Sketch

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

Problem 3.16: Showing a Power is Real

Let $z = \sqrt{3} - i$. Show that z^6 is real.

Hint: Convert to polar form: $z = 2(\cos(-\pi/6) + i \sin(-\pi/6))$.

Solution 3.16: Sketch

$$z^6 = 2^6 (\cos(-\pi) + i \sin(-\pi)) = 64(-1 + 0i) = -64, \text{ which is real.}$$

Problem 3.17: Principal Argument

Evaluate $\text{Arg}(z)$ for $z = -\sqrt{3} + i$.

Hint: z is in the second quadrant. Use $\tan \theta = \frac{\text{opposite}}{\text{adjacent}}$.

Solution 3.17: Sketch

Reference angle is $\pi/6$. Since z is in Q2, $\text{Arg}(z) = \pi - \pi/6 = \frac{5\pi}{6}$.

3.2 Medium Complex Numbers Problems

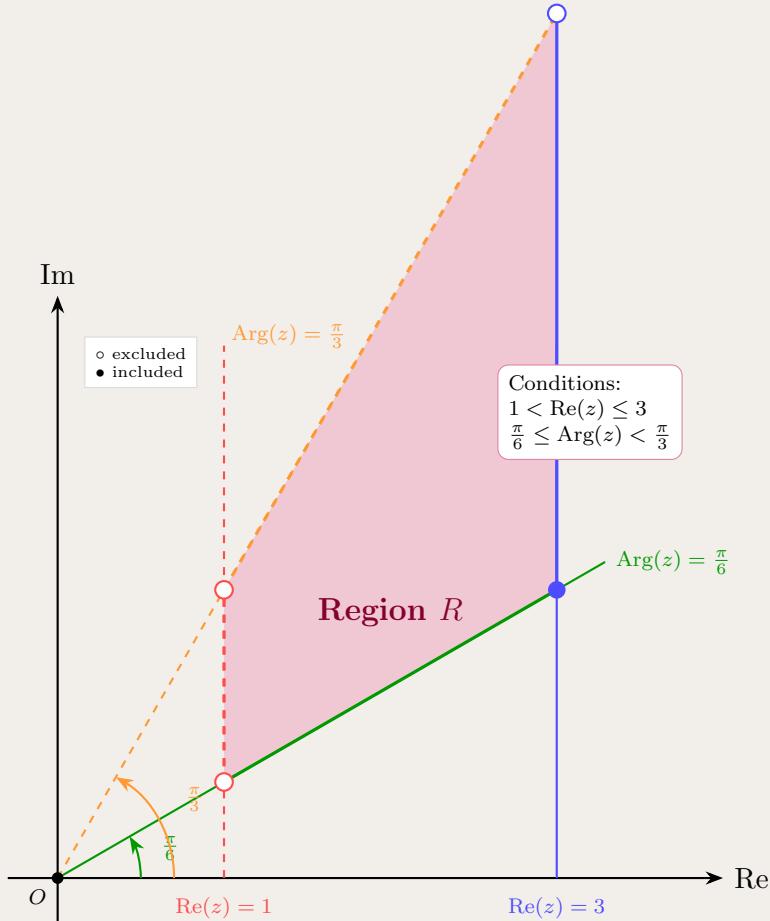
Problem 3.18: Region with Real and Argument Constraints

Let R be the region in the complex plane defined by $1 < \text{Re}(z) \leq 3$ and $\frac{\pi}{6} \leq \text{Arg}(z) < \frac{\pi}{3}$. Sketch this region.

Hint: The region is bounded by two vertical lines ($x = 1$ and $x = 3$) and two rays from the origin at angles $\pi/6$ and $\pi/3$.

Solution 3.18: Sketch

Draw vertical lines at $x = 1$ (dashed, excluded) and $x = 3$ (solid, included). Draw rays from origin at angles 30° (solid) and 60° (dashed). The region is the intersection in the first quadrant.



Problem 3.19: Statement Analysis

Which statement about complex numbers is true?

- (A) For $z = x + iy$, the argument is given by $\arg(z) = \arctan(y/x)$ for all $z \neq 0$.
- (B) For any two complex numbers z_1 and z_2 , we have $\operatorname{Arg}(z_1 z_2) = \operatorname{Arg}(z_1) + \operatorname{Arg}(z_2)$.
- (C) If two complex numbers have the same modulus and their arguments satisfy $\theta_1 = \theta_2 + 2\pi k$ for some integer k , then they are equal (modulo 2π).
- (D) For $z = x + iy$ with $x > 0$, the argument is $\arg(z) = \arctan(y/x)$.

Hint: Check each statement. Remember that $\operatorname{Arg}(z_1 z_2) = \operatorname{Arg}(z_1) + \operatorname{Arg}(z_2)$ only modulo 2π .

Solution 3.19: Sketch

- **(A) False:** The formula $\arg(z) = \arctan(y/x)$ doesn't account for the quadrant. For example, if $z = -1 + i$, then $\arctan(-1) = -\pi/4$, but the actual argument is $3\pi/4$ (in the second quadrant).
- **(B) False:** Principal argument addition requires modulo 2π adjustment. For instance, if $\text{Arg}(z_1) = 3\pi/4$ and $\text{Arg}(z_2) = 3\pi/4$, then $\text{Arg}(z_1) + \text{Arg}(z_2) = 3\pi/2$, but we need to adjust to the principal range $(-\pi, \pi]$, giving $\text{Arg}(z_1 z_2) = -\pi/2$.
- **(C) True (with proper interpretation):** If $|z_1| = |z_2|$ and $\arg(z_1) = \arg(z_2) + 2\pi k$ for integer k , then $z_1 = z_2$ since arguments that differ by $2\pi k$ represent the same direction.
- **(D) True (but limited):** This is correct when $x > 0$ (first and fourth quadrants), as the arctan function gives the correct argument in these quadrants without adjustment.

Answer: The best answer is **(D)** for its specific domain, though **(C)** is also correct if “equality” means modulo 2π . Statement **(D)** is the most straightforward true statement.

Problem 3.20: Roots of Unity Application

Suppose that $x + \frac{1}{x} = -1$. What is the value of $x^{2016} + \frac{1}{x^{2016}}$?

Hint: Solve $x^2 + x + 1 = 0$ to find $x = e^{\pm i2\pi/3}$. These are cube roots of unity.

Solution 3.20: Sketch

$x^2 + x + 1 = 0$ gives $x = e^{\pm i2\pi/3}$. Since $x^3 = 1$, we have $x^{2016} = x^{3 \cdot 672} = 1$. Thus $x^{2016} + \frac{1}{x^{2016}} = 1 + 1 = 2$.

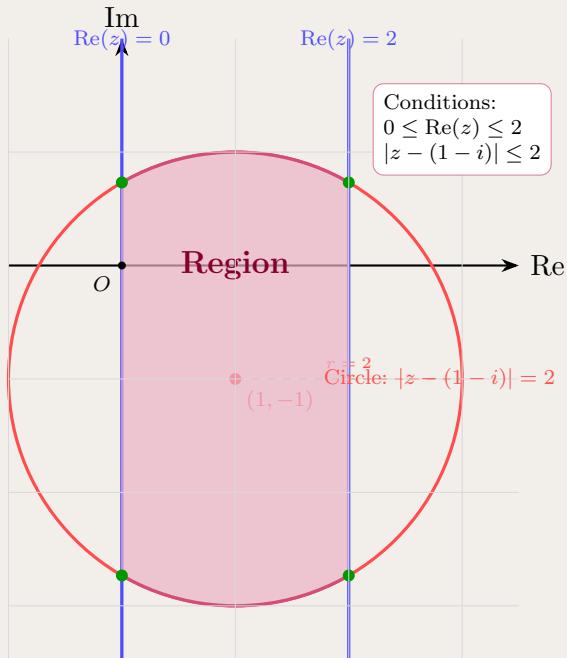
Problem 3.21: Shading a Region

On an Argand diagram, shade the region where $0 \leq \text{Re}(z) \leq 2$ and $|z - (1 - i)| \leq 2$ both hold.

Hint: The first inequality is a vertical strip. The second is a disk centred at $(1, -1)$ with radius 2.

Solution 3.21: Sketch

Draw vertical lines at $x = 0$ and $x = 2$. Draw circle centered at $(1, -1)$ with radius 2. Shade the intersection.



Problem 3.22: Modulus-Argument Division

Given $\frac{1+\sqrt{3}i}{1+i} = \frac{1+\sqrt{3}}{2} + \frac{\sqrt{3}-1}{2}i$, express $\frac{1+i\sqrt{3}}{1+i}$ in modulus-argument form by converting both numerator and denominator.

Hint: $|1 + i\sqrt{3}| = 2$, $\arg(1 + i\sqrt{3}) = \pi/3$; $|1 + i| = \sqrt{2}$, $\arg(1 + i) = \pi/4$.

Solution 3.22: Sketch

$$\frac{1+i\sqrt{3}}{1+i} = \frac{2}{\sqrt{2}} \left(\cos\left(\frac{\pi}{3} - \frac{\pi}{4}\right) + i \sin\left(\frac{\pi}{3} - \frac{\pi}{4}\right) \right) = \sqrt{2} \left(\cos\frac{\pi}{12} + i \sin\frac{\pi}{12} \right).$$

Problem 3.23: Power in Polar Form

Let $\beta = 1 - i\sqrt{3}$. Express β^5 in modulus-argument form.

Hint: $|\beta| = 2$, $\arg(\beta) = -\pi/3$.

Solution 3.23: Sketch

$\beta = 2(\cos(-\pi/3) + i \sin(-\pi/3))$. Then $\beta^5 = 32(\cos(-5\pi/3) + i \sin(-5\pi/3)) = 32(\cos(\pi/3) + i \sin(\pi/3))$.

Problem 3.24: Deriving Trigonometric Value

Using previous results, find the exact value of $\sin \frac{\pi}{12}$.

Hint: From $\frac{\beta}{\alpha} = \sqrt{2}(\cos \frac{\pi}{12} + i \sin \frac{\pi}{12})$, compute explicitly or use half-angle formulas.

Solution 3.24: Sketch

$\frac{\pi}{12} = \frac{\pi}{3} - \frac{\pi}{4}$. Using angle subtraction: $\sin \frac{\pi}{12} = \sin \frac{\pi}{3} \cos \frac{\pi}{4} - \cos \frac{\pi}{3} \sin \frac{\pi}{4} = \frac{\sqrt{3}}{2} \cdot \frac{\sqrt{2}}{2} - \frac{1}{2} \cdot \frac{\sqrt{2}}{2} = \frac{\sqrt{6} - \sqrt{2}}{4}$.

Problem 3.25: Marking Rotated Point

A point P represents the complex number $z = 3 + 2i$ on the Argand diagram. Mark the point R representing iz .

Hint: Multiply by i rotates 90° counterclockwise. If $z = a + bi$, then $iz = i(a + bi) = -b + ai$.

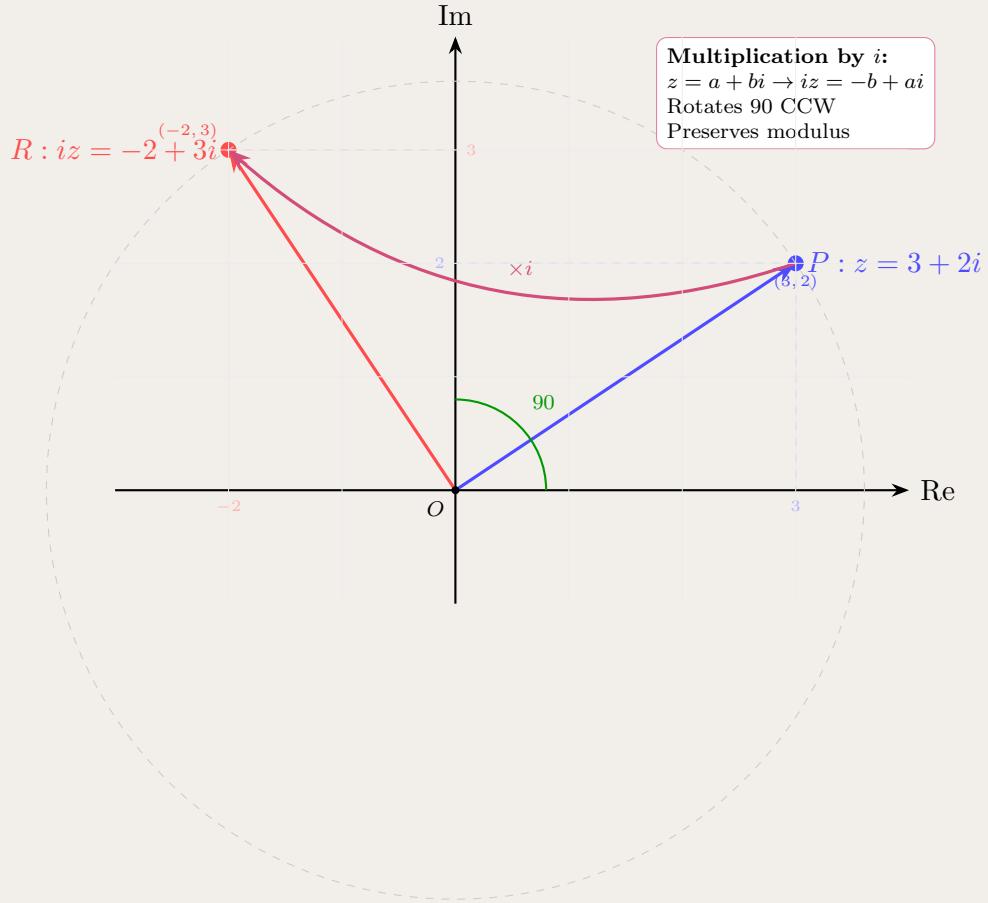
Solution 3.25: Sketch

If z is at (a, b) , then iz is at $(-b, a)$. Draw accordingly.

For $z = 3 + 2i$ at point $(3, 2)$:

$$iz = i(3 + 2i) = 3i + 2i^2 = 3i - 2 = -2 + 3i$$

So R is at $(-2, 3)$.



Key observation: Multiplying by i rotates any complex number by 90 counterclockwise while keeping the same distance from the origin.

Problem 3.26: Conjugate Root Property

$2 + i$ is a root of $P(z) = z^3 + rz^2 + sz + 20$ where r, s are real. State why $2 - i$ is also a root.

Hint: Polynomials with real coefficients have complex roots in conjugate pairs.

Solution 3.26: Sketch

Since $P(z)$ has real coefficients, if $2 + i$ is a root, then $\overline{2+i} = 2 - i$ must also be a root.

Problem 3.27: Factorizing Over Reals

Factorise $P(z) = z^3 + rz^2 + sz + 20$ over the real numbers, given roots $2+i$ and $2-i$.

$$\text{Hint: } z - (2+i) = (z-2)-i \quad z - (2-i) = (z-2)+i$$

Solution 3.27: Sketch

$(z - 2 - i)(z - 2 + i) = z^2 - 4z + 5$. Divide $P(z)$ by $z^2 - 4z + 5$ to find the third factor.
 $P(z) = (z^2 - 4z + 5)(z + 4)$ after polynomial division.

Problem 3.28: Vector Addition Point

Points P and Q represent the complex numbers $z = 2 + i$ and $w = 1 + 3i$ respectively on the Argand diagram. Mark point T representing $z + w$.

Hint: Use parallelogram law: T is the fourth vertex of parallelogram $OPTQ$ where O is the origin.

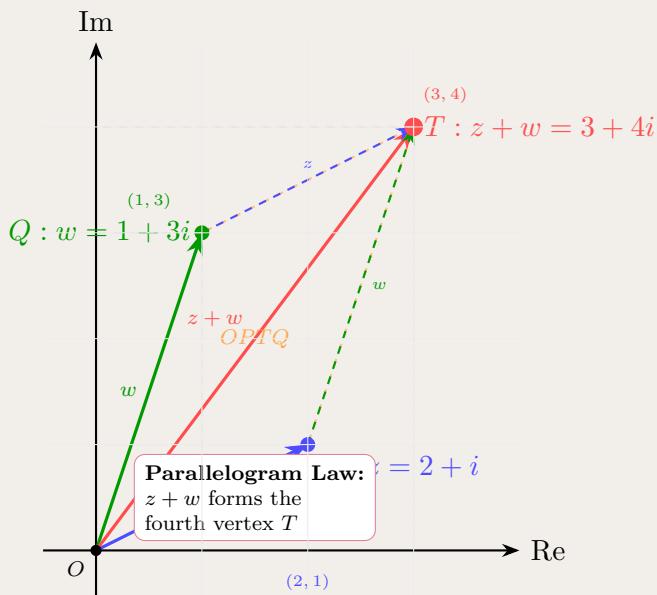
Solution 3.28: Sketch

From O to P is vector z , from O to Q is vector w . The sum $z + w$ is at the opposite corner of the parallelogram.

For $z = 2 + i$ and $w = 1 + 3i$:

$$z + w = (2 + i) + (1 + 3i) = 3 + 4i$$

So T is at $(3, 4)$.



Key observations:

- The parallelogram $OPTQ$ has OP parallel to QT (both represent vector z)
- Similarly, OQ is parallel to PT (both represent vector w)
- Vector addition: starting from O , go to P (add z), then to T (add w)
- Alternatively: starting from O , go to Q (add w), then to T (add z)
- The diagonal OT represents the sum $z + w$

Problem 3.29: Sum in Polar Form

Let $z = -2 - 2i$ and $w = 3 + i$. Express $z + w$ in modulus-argument form.

Hint: First find $z + w = 1 - i$, then convert to polar.

Solution 3.29: Sketch

$$z + w = 1 - i. |z + w| = \sqrt{2}, \arg(z + w) = -\pi/4. \text{ So } z + w = \sqrt{2}(\cos(-\pi/4) + i \sin(-\pi/4)).$$

Problem 3.30: Division in Mixed Form

Express $\frac{z}{w}$ in form $x + iy$ where $z = -2 - 2i$, $w = 3 + i$.

$$\text{Hint: } \frac{z}{w} = \frac{(3-i)(3-i)}{(-2-2i)(3-i)}.$$

Solution 3.30: Sketch

$$\frac{(-2-2i)(3-i)}{10} = \frac{-6+2i-6i+2i^2}{10} = \frac{-8-4i}{10} = -\frac{4}{5} - \frac{2}{5}i.$$

Problem 3.31: Sketching with Argument and Circle

Sketch the region: $-\frac{\pi}{4} \leq \arg z \leq 0$ and $|z - (1 - i)| \leq 1$.

Hint: The first is a wedge in the fourth quadrant. The second is a disk centered at $(1, -1)$.

Solution 3.31: Sketch

Draw rays at angles -45° and 0° from origin. Draw circle centered at $(1, -1)$ radius 1. Shade intersection.

Problem 3.32: High Power via De Moivre

Express z^9 in form $x + iy$ for $z = \sqrt{3} - i$.

$$\text{Hint: } z = 2(\cos(-\pi/6) + i \sin(-\pi/6)).$$

Solution 3.32: Sketch

$$z^9 = 2^9(\cos(-3\pi/2) + i \sin(-3\pi/2)) = 512(0 + i) = 512i.$$

Problem 3.33: Polar Form of Specific Number

Write $z = -1 + i\sqrt{3}$ in modulus-argument form.

$$\text{Hint: } |z| = 2, z \text{ is in the second quadrant with reference angle } \pi/3.$$

Solution 3.33: Sketch

$$z = 2(\cos(2\pi/3) + i \sin(2\pi/3)).$$

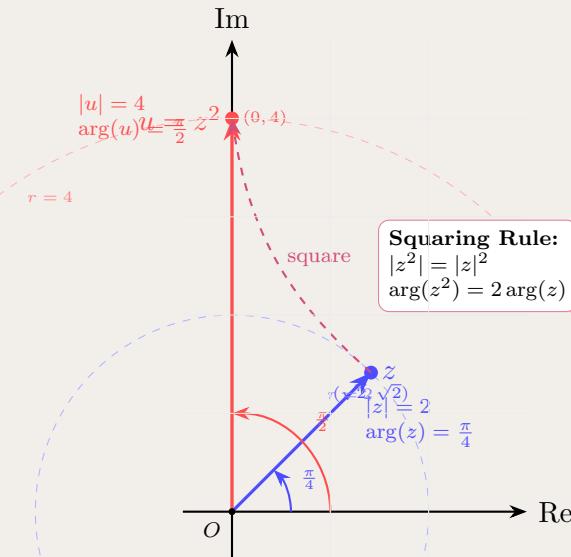
Problem 3.34: Plotting a Squared Number

Given $|z| = 2$, $\arg(z) = \frac{\pi}{4}$, plot $u = z^2$.

Hint: $|u|^2 = 4$, $\arg(u) = 2\arg(z) = \pi/2$.

Solution 3.34: Sketch

u has modulus 4 and argument $\pi/2$, so $u = 4i$. Plot at $(0, 4)$.



3.3 Advanced Complex Numbers Problems

Problem 3.35: Complex Region with Exclusion

Sketch the region on the Argand diagram where $|z - \bar{z}| < 2$ and $|z - 1| \geq 1$ hold simultaneously.

Hint: $|z - \bar{z}| = |2iy| = 2|y|$, so the first inequality gives $|y| < 1$. The second is the exterior of a circle.

Solution 3.35: Sketch

The region $|y| < 1$ is a horizontal strip $-1 < y < 1$. The region $|z - 1| \geq 1$ is outside the circle centered at $(1, 0)$ with radius 1. Shade the intersection: horizontal strip with circular hole.

Problem 3.36: Isosceles Right Triangle

Triangle ABC is represented by z_1, z_2, z_3 . It is isosceles and right-angled at B . Explain why $(z_1 - z_2)^2 = -(z_3 - z_2)^2$.

Hint: The vectors BA and BC are perpendicular and equal in length. Multiplication by i rotates by 90° .

Solution 3.36: Sketch

$BA = z_1 - z_2$, $BC = z_3 - z_2$. Since $BA \perp BC$ and $|BA| = |BC|$, we have $BA = \pm i \cdot BC$. Squaring: $(z_1 - z_2)^2 = (\pm i)^2(z_3 - z_2)^2 = -1 \cdot (z_3 - z_2)^2$.

Problem 3.37: Square from Triangle

Three vertices of a square $ABCD$ in the complex plane are represented by complex numbers z_1 (point A), z_2 (point B), and z_3 (point C). Given that consecutive sides of a square are perpendicular and equal in length, find the complex number z_4 representing vertex D in terms of z_1, z_2, z_3 .

Hint: Since $ABCD$ is a square, side AB is perpendicular to side BC , and $|AB| = |BC|$. This means $BA = i \cdot BC$ (or $-i \cdot BC$). Use the same relationship for sides CD and DA .

Solution 3.37: Sketch

For a square $ABCD$, consecutive sides are equal in length and perpendicular. The vector from B to A is $z_1 - z_2$, and from B to C is $z_3 - z_2$. Since $BA \perp BC$ and $|BA| = |BC|$, we have:

$$z_1 - z_2 = i(z_3 - z_2) \quad (\text{rotating } BC \text{ by } 90 \text{ counterclockwise})$$

Similarly, for the square to close, the vector from C to D must equal the vector from B to C rotated 90:

$$z_4 - z_3 = i(z_2 - z_3)$$

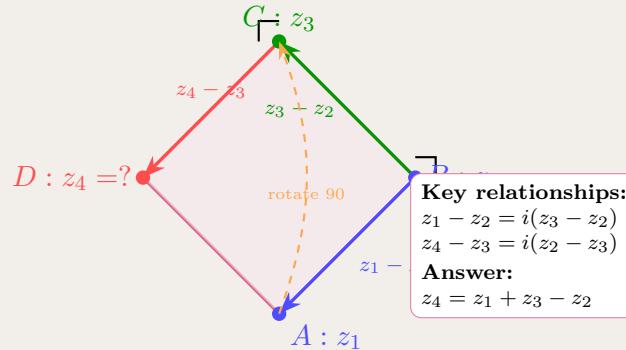
Solving for z_4 :

$$\begin{aligned} z_4 &= z_3 + i(z_2 - z_3) \\ &= z_3 + iz_2 - iz_3 \\ &= z_2 \cdot i + z_3(1 - i) \\ &= iz_2 + z_3(1 - i) \end{aligned}$$

Alternative formula: Using the parallelogram property, we can also write:

$$z_4 = z_1 + z_3 - z_2$$

This works because $\vec{AD} = \vec{BC}$, so $z_4 - z_1 = z_3 - z_2$.



Verification: Both formulas are equivalent:

$$\begin{aligned} iz_2 + z_3(1 - i) &= iz_2 + z_3 - iz_3 \\ &= z_3 + i(z_2 - z_3) \end{aligned}$$

And using $z_1 - z_2 = i(z_3 - z_2)$, we get $z_1 = z_2 + i(z_3 - z_2) = iz_3 + z_2(1 - i)$. Therefore: $z_4 = z_1 + z_3 - z_2$

Problem 3.38: Factoring Polynomial

Express $P(x) = x^4 - 12x^3 + 59x^2 - 138x + 130$ as product of quadratic factors, given roots $3 + i$ and $3 + 2i$.

Hint: The roots are $3 \pm i$ and $3 \mp 2i$. Group conjugate pairs.

Solution 3.38: Sketch

$$(x - (3 + i))(x - (3 - i)) = (x - 3)^2 + 1 = x^2 - 6x + 10. (x - (3 + 2i))(x - (3 - 2i)) = (x - 3)^2 + 4 = x^2 - 6x + 13. \text{ Thus } P(x) = (x^2 - 6x + 10)(x^2 - 6x + 13).$$

Problem 3.39: Real Root Count

Deduce that $x^4 - 3x^3 + 5x^2 + 7x - 8 = 0$ has exactly two real roots.

Hint: A degree-4 polynomial with real coefficients has either 0, 2, or 4 real roots. Check behavior or use Descartes' rule.

Solution 3.39: Sketch

Complex roots come in conjugate pairs. If there are 4 complex roots, they form 2 pairs, leaving 0 real roots. If 1 pair of complex roots, then 2 real roots. Since the polynomial has sign changes, it must have at least one positive real root. Testing values or using intermediate value theorem confirms exactly 2 real roots.

Problem 3.40: Vector Addition and Angles

Points P_0, P_1, P_2, P_3 correspond to $z_0, z_0 + z_1, z_0 + z_1 + z_2, \dots$ where $z_n = \cos(\alpha + n\beta) + i \sin(\alpha + n\beta)$. Using vector addition, explain why external angles $\theta_0 = \theta_1 = \theta_2 = \beta$.

Hint: Each z_n is a unit vector at angle $\alpha + n\beta$. The angle between consecutive vectors is constant.

Solution 3.40: Sketch

Vector z_n has argument $\alpha + n\beta$, and z_{n+1} has argument $\alpha + (n+1)\beta$. The difference is β , which is the external angle between consecutive segments. Thus all external angles equal β .

Problem 3.41: Modulus via Trigonometry

Show $|z| = 2 \sin \theta$ for $z = 1 - \cos 2\theta + i \sin 2\theta$.

Hint: Use $1 - \cos 2\theta = 2 \sin^2 \theta$ and $\sin 2\theta = 2 \sin \theta \cos \theta$.

Solution 3.41: Sketch

$|z|^2 = (1 - \cos 2\theta)^2 + \sin^2 2\theta = (2 \sin^2 \theta)^2 + (2 \sin \theta \cos \theta)^2 = 4 \sin^4 \theta + 4 \sin^2 \theta \cos^2 \theta = 4 \sin^2 \theta (\sin^2 \theta + \cos^2 \theta) = 4 \sin^2 \theta$. Thus $|z| = 2|\sin \theta|$.

Problem 3.42: Euler's Formula Identity

Show $e^{in\theta} + e^{-in\theta} = 2 \cos(n\theta)$.

Hint: Use $e^{i\phi} = \cos \phi + i \sin \phi$.

Solution 3.42: Sketch

$e^{in\theta} = \cos(n\theta) + i \sin(n\theta)$ and $e^{-in\theta} = \cos(n\theta) - i \sin(n\theta)$. Adding: $e^{in\theta} + e^{-in\theta} = 2 \cos(n\theta)$.

Problem 3.43: Modulus of Sum

Let $z = e^{i\pi/6}$, $w = e^{i3\pi/4}$. Show $|z + w|^2 = \frac{4-\sqrt{6}+\sqrt{2}}{2}$.

Hint: $m\underline{z} + \underline{m}z + \underline{z}|m| + \underline{z}|z| = (\underline{m} + \underline{z})(m + z) = (\underline{m+z})(m+z) = \underline{z}|m+z|$.

Solution 3.43: Sketch

$|z| = |w| = 1$. $z\bar{w} = e^{i(\pi/6-3\pi/4)} = e^{-i7\pi/12}$, $\bar{z}w = e^{i7\pi/12}$. Thus $|z + w|^2 = 2 + 2 \cos(7\pi/12) = 2(1 + \cos(7\pi/12))$. Evaluate $\cos(7\pi/12) = \cos(105^\circ) = -\sin(15^\circ) = -\frac{\sqrt{6}-\sqrt{2}}{4}$. Result follows.

Problem 3.44: Equilateral Triangle

Let z_1 be a non-zero complex number represented by point A on the Argand diagram, and let $z_2 = e^{i\pi/3}z_1$ be represented by point B . The origin is represented by point O . Prove that triangle $\triangle OAB$ is equilateral.

Hint: Multiplication by $e^{i\pi/3}$ rotates z_1 by angle $\pi/3 = 60^\circ$ while preserving its modulus. Therefore $|z_1| = |z_2|$ and the angle $\angle AOB = \pi/3$.

Solution 3.44: Sketch

We need to show that all three sides of triangle OAB are equal.

Given: $z_2 = e^{i\pi/3} z_1$

Step 1: Show two sides are equal

Since multiplication by $e^{i\pi/3}$ preserves modulus:

$$|OA| = |z_1| \quad \text{and} \quad |OB| = |z_2| = |e^{i\pi/3} z_1| = |e^{i\pi/3}| \cdot |z_1| = 1 \cdot |z_1| = |z_1|$$

Therefore: $|OA| = |OB| = |z_1|$

Step 2: Find the angle at O

Since $z_2 = e^{i\pi/3} z_1$, the argument of z_2 is:

$$\arg(z_2) = \arg(e^{i\pi/3} z_1) = \arg(e^{i\pi/3}) + \arg(z_1) = \frac{\pi}{3} + \arg(z_1)$$

Therefore, the angle $\angle AOB = \frac{\pi}{3} = 60$

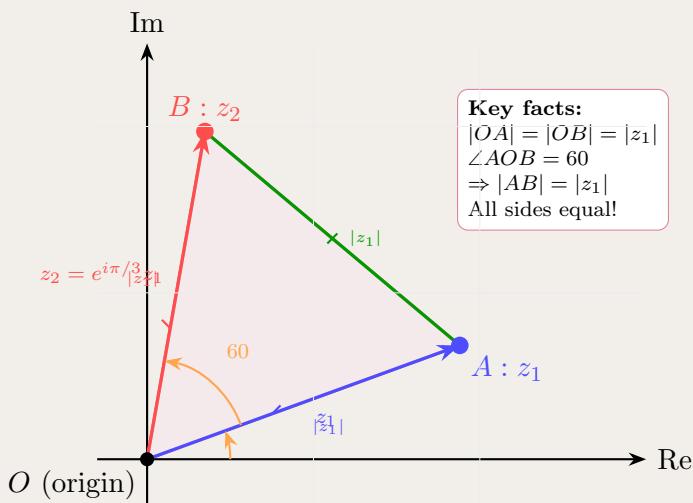
Step 3: Calculate the third side using law of cosines

For triangle OAB :

$$\begin{aligned} |AB|^2 &= |OA|^2 + |OB|^2 - 2|OA||OB|\cos(\pi/3) \\ &= |z_1|^2 + |z_1|^2 - 2|z_1|^2 \cdot \frac{1}{2} \\ &= 2|z_1|^2 - |z_1|^2 \\ &= |z_1|^2 \end{aligned}$$

Therefore: $|AB| = |z_1|$

Conclusion: $|OA| = |OB| = |AB| = |z_1|$, so triangle OAB is equilateral.



Alternative approach: We can also compute $|AB| = |z_2 - z_1|$ directly:

$$\begin{aligned} |z_2 - z_1| &= |e^{i\pi/3} z_1 - z_1| \\ &= |z_1| |e^{i\pi/3} - 1| \\ &= |z_1| \cdot |(\cos 60 + i \sin 60) - 1| \\ &= |z_1| \cdot |(1/2 + i\sqrt{3}/2) - 1| \\ &= |z_1| \cdot |-1/2 + i\sqrt{3}/2| \\ &= |z_1| \cdot \sqrt{1/4 + 3/4} \\ &= |z_1| \end{aligned}$$

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This confirms $|AB| = |z_1|$, completing the proof.

Problem 3.45: Algebraic Identity

Consider an equilateral triangle $\triangle OAB$ where O is the origin, A represents complex number z_1 , and B represents $z_2 = e^{i\pi/3}z_1$ (i.e., z_2 is obtained by rotating z_1 by 60°). Prove the algebraic identity:

$$z_1^2 + z_2^2 = z_1 z_2$$

Hint: Let $w = e^{i\pi/3}$, so $z_2 = wz_1$. Show that w satisfies $w^2 - w + 1 = 0$ by using the fact that $w^3 = e^{i\pi} = -1$.

Solution 3.45: Sketch

Let $\omega = e^{i\pi/3}$ (a primitive 6th root of unity). Then $z_2 = \omega z_1$.

Left-hand side:

$$\begin{aligned}z_1^2 + z_2^2 &= z_1^2 + (\omega z_1)^2 \\&= z_1^2 + \omega^2 z_1^2 \\&= z_1^2(1 + \omega^2)\end{aligned}$$

Right-hand side:

$$\begin{aligned}z_1 z_2 &= z_1 \cdot \omega z_1 \\&= \omega z_1^2\end{aligned}$$

To prove: We need to show that $1 + \omega^2 = \omega$, or equivalently:

$$\omega^2 - \omega + 1 = 0$$

Key observation: Since $\omega = e^{i\pi/3}$, we have:

$$\omega^3 = e^{i\pi/3 \cdot 3} = e^{i\pi} = -1$$

Therefore:

$$\omega^3 + 1 = 0$$

This factors as:

$$(\omega + 1)(\omega^2 - \omega + 1) = 0$$

Since $\omega = e^{i\pi/3} = \cos 60 + i \sin 60 = \frac{1}{2} + i \frac{\sqrt{3}}{2} \neq -1$, we must have:

$$\omega^2 - \omega + 1 = 0$$

Therefore $1 + \omega^2 = \omega$, which gives us:

$$z_1^2(1 + \omega^2) = z_1^2 \cdot \omega = \omega z_1^2 = z_1 z_2$$

Thus: $z_1^2 + z_2^2 = z_1 z_2 \quad \square$

Alternative direct verification: We can also verify by direct calculation:

$$\begin{aligned}\omega^2 &= e^{i2\pi/3} = \cos 120 + i \sin 120 = -\frac{1}{2} + i \frac{\sqrt{3}}{2} \\1 + \omega^2 &= 1 + \left(-\frac{1}{2} + i \frac{\sqrt{3}}{2}\right) = \frac{1}{2} + i \frac{\sqrt{3}}{2} = \omega \quad \checkmark\end{aligned}$$

Problem 3.46: Finding Non-Real Roots

Find the two complex roots of $P(x) = x^5 - 10x^2 + 15x - 6$.

Hint: Test for rational roots first (like $x = 1$). Factor out linear factors, then solve the remaining polynomial.

Solution 3.46: Sketch

$P(1) = 1 - 10 + 15 - 6 = 0$, so $(x - 1)$ is a factor. Polynomial division gives $P(x) = (x - 1)(x^4 + x^3 + x^2 - 9x + 6)$. Continue factoring or use numerical/algebraic methods to find complex roots.

Problem 3.47: Expansion Result

Using De Moivre's theorem and the binomial expansion, derive the formula for $\cos 5\theta$ in terms of $\cos \theta$. Hence show that:

$$\cos 5\theta = 16 \cos^5 \theta - 20 \cos^3 \theta + 5 \cos \theta$$

Hint: Use Euler's formula: $(\cos \theta + i \sin \theta)^5 = \cos 5\theta + i \sin 5\theta$. Expand the left side using the binomial theorem, then equate real parts. Express $\sin^2 \theta$ in terms of $\cos \theta$ using $\sin^2 \theta = 1 - \cos^2 \theta$.

Solution 3.47: Sketch

By De Moivre's theorem:

$$(\cos \theta + i \sin \theta)^5 = \cos 5\theta + i \sin 5\theta$$

Expand the left side using binomial theorem:

$$\begin{aligned} (\cos \theta + i \sin \theta)^5 &= \sum_{k=0}^5 \binom{5}{k} \cos^{5-k} \theta (i \sin \theta)^k \\ &= \binom{5}{0} \cos^5 \theta + \binom{5}{1} \cos^4 \theta (i \sin \theta) + \binom{5}{2} \cos^3 \theta (i \sin \theta)^2 \\ &\quad + \binom{5}{3} \cos^2 \theta (i \sin \theta)^3 + \binom{5}{4} \cos \theta (i \sin \theta)^4 + \binom{5}{5} (i \sin \theta)^5 \\ &= \cos^5 \theta + 5i \cos^4 \theta \sin \theta - 10 \cos^3 \theta \sin^2 \theta \\ &\quad - 10i \cos^2 \theta \sin^3 \theta + 5 \cos \theta \sin^4 \theta + i \sin^5 \theta \end{aligned}$$

Separate real and imaginary parts:

Real part:

$$\operatorname{Re} = \cos^5 \theta - 10 \cos^3 \theta \sin^2 \theta + 5 \cos \theta \sin^4 \theta$$

This equals $\cos 5\theta$.

Express in terms of $\cos \theta$ only:

Use $\sin^2 \theta = 1 - \cos^2 \theta$:

$$\begin{aligned} \cos 5\theta &= \cos^5 \theta - 10 \cos^3 \theta (1 - \cos^2 \theta) + 5 \cos \theta (1 - \cos^2 \theta)^2 \\ &= \cos^5 \theta - 10 \cos^3 \theta + 10 \cos^5 \theta + 5 \cos \theta (1 - 2 \cos^2 \theta + \cos^4 \theta) \\ &= \cos^5 \theta - 10 \cos^3 \theta + 10 \cos^5 \theta + 5 \cos \theta - 10 \cos^3 \theta + 5 \cos^5 \theta \\ &= (1 + 10 + 5) \cos^5 \theta + (-10 - 10) \cos^3 \theta + 5 \cos \theta \\ &= 16 \cos^5 \theta - 20 \cos^3 \theta + 5 \cos \theta \end{aligned}$$

Therefore: $\cos 5\theta = 16 \cos^5 \theta - 20 \cos^3 \theta + 5 \cos \theta \quad \square$

Problem 3.48: Symmetry Identity

Show $\alpha^k + \alpha^{-k} = 2 \cos k\theta$ where $\alpha = \cos \theta + i \sin \theta$.

Hint: $e^{i\theta} = \cos \theta + i \sin \theta$ and $e^{-i\theta} = \cos \theta - i \sin \theta$

Solution 3.48: Sketch

$\alpha^k = e^{ik\theta} = \cos k\theta + i \sin k\theta$, $\alpha^{-k} = e^{-ik\theta} = \cos k\theta - i \sin k\theta$. Adding: $\alpha^k + \alpha^{-k} = 2 \cos k\theta$.

Problem 3.49: Equilateral Triangle Centroid

Let $\triangle ABC$ be an equilateral triangle with vertices A, B, C represented by complex numbers a, b, c respectively, oriented anticlockwise. Let $\omega = e^{i2\pi/3} = \cos 120 + i \sin 120$ be a primitive cube root of unity. Prove that the centroid of the triangle is at the origin if and only if:

$$a + b\omega + c\omega^2 = 0$$

Hint: For an equilateral triangle centred at the origin, the vertices are related by 120 rotations. Use the fact that $\omega = e^{i2\pi/3}$ satisfies $\omega^3 = 1$ and $1 + \omega + \omega^2 = 0$.

Solution 3.49: Sketch

Key facts about $\omega = e^{i2\pi/3}$:

- $\omega^3 = e^{i2\pi} = 1$ (cube root of unity)
- $1 + \omega + \omega^2 = 0$ (sum of cube roots of unity)
- $\omega = -\frac{1}{2} + i\frac{\sqrt{3}}{2}$

If the triangle is centered at origin:

For an equilateral triangle centered at the origin with one vertex at a , the other two vertices are obtained by rotating by 120 and 240:

$$b = \omega a \quad \text{and} \quad c = \omega^2 a$$

Now compute:

$$\begin{aligned} a + b\omega + c\omega^2 &= a + (\omega a) \cdot \omega + (\omega^2 a) \cdot \omega^2 \\ &= a + \omega^2 a + \omega^4 a \\ &= a(1 + \omega^2 + \omega^4) \end{aligned}$$

Since $\omega^3 = 1$, we have $\omega^4 = \omega^3 \cdot \omega = 1 \cdot \omega = \omega$.

Therefore:

$$a + b\omega + c\omega^2 = a(1 + \omega^2 + \omega) = a(1 + \omega + \omega^2)$$

Using the fundamental identity $1 + \omega + \omega^2 = 0$:

$$a + b\omega + c\omega^2 = a \cdot 0 = 0$$

Conversely: If $a + b\omega + c\omega^2 = 0$ and the triangle is equilateral, then its centroid is at the origin.

The centroid is at $\frac{a+b+c}{3}$. For an equilateral triangle with the given property, we can show:

$$a + b + c = 0$$

This follows because if $a + b\omega + c\omega^2 = 0$, and we also have the relations for an equilateral triangle, then the centroid must be at the origin.

Therefore: $a + b\omega + c\omega^2 = 0 \quad \square$

Geometric interpretation: This identity expresses the fact that in an equilateral triangle centered at the origin, the weighted sum of the vertices (with weights 1, ω , ω^2) is zero, reflecting the rotational symmetry of the configuration.

4 Conclusion

Complex numbers are a core component of the HSC Mathematics Extension 2 course. Mastery comes from repeated, reflective practice across all forms—Cartesian, polar, and exponential—and understanding their geometric interpretations. Use these problems to sharpen the ability to convert between forms, apply De Moivre's theorem, interpret loci geometrically, and communicate complete mathematical reasoning. Best of luck with your studies and HSC examinations!

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Repository: <https://github.com/vuhung16au/math-olympiad-ml/tree/main/HSC-ComplexNumbers>