

# HSC Math Extension 2: Last Resorts Mastery

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# 1 Introduction

## 1.1 Project Overview

This booklet compiles the most challenging problems from HSC Mathematics Extension 2 examinations—the notorious Problem 16, as we call them “Last Resort.” These problems represent the pinnacle of high school mathematics, typically combining multiple advanced topics and requiring sophisticated problem-solving techniques. Every problem showcases the depth and complexity expected at the highest level of the HSC Mathematics curriculum.

The collection draws from authentic examination problems that have challenged Extension 2 students over many years. Each problem has been carefully selected to represent the diverse range of mathematical concepts and proof techniques that appear in Problem 16, from advanced inequalities and complex number theory to vector optimization and differential geometry applications.

## 1.2 What Makes Problem 16 Special

Problem 16 is uniquely challenging because it:

- Combines multiple mathematical topics within a single problem
- Requires advanced proof techniques and mathematical maturity
- Often involves multi-part questions that build complexity progressively
- Tests both computational skills and conceptual understanding
- Demands clear mathematical communication and rigorous reasoning

## 1.3 Target Audience

This booklet is designed for Extension 2 students who want to:

- Master the most challenging problems in the HSC curriculum
- Develop advanced problem-solving strategies
- Build confidence in tackling complex multi-step problems
- Understand how to approach unfamiliar mathematical scenarios
- Prepare thoroughly for the demands of Problem 16 in examinations

## 1.4 How to Use This Booklet

- **Study the Fundamentals:** Review key theorems and techniques
- **Attempt Problems Independently:** Try each problem without looking at solutions first
- **Part 1 Strategy:** Compare your work against solutions to understand model reasoning
- **Part 2 Approach:** Use upside-down hints sparingly, then review concise solutions
- **Practice Multiple Times:** Rework problems from memory to build technique mastery
- **Focus on Communication:** Pay attention to how mathematical arguments are structured and presented

## 2 Fundamentals Review

### 2.1 Key Inequalities

Problem 16 frequently employs fundamental inequalities as building blocks for more complex arguments.

#### 2.1.1 Arithmetic-Geometric Mean (AM-GM) Inequality

##### Theorem 0.1: AM-GM Inequality

For positive real numbers  $a_1, a_2, \dots, a_n$ :

$$\frac{a_1 + a_2 + \dots + a_n}{n} \geq \sqrt[n]{a_1 a_2 \dots a_n}$$

Equality occurs if and only if  $a_1 = a_2 = \dots = a_n$ .

##### Theorem 0.2: Weighted AM-GM Inequality

For positive real numbers  $a_1, a_2, \dots, a_n$  and positive weights  $w_1, w_2, \dots, w_n$  with  $w_1 + w_2 + \dots + w_n = 1$ :

$$w_1 a_1 + w_2 a_2 + \dots + w_n a_n \geq a_1^{w_1} a_2^{w_2} \dots a_n^{w_n}$$

#### 2.1.2 Cauchy-Schwarz Inequality

##### Theorem 0.3: Cauchy-Schwarz Inequality

For vectors  $\mathbf{u}$  and  $\mathbf{v}$  in  $\mathbb{R}^n$ :

$$|\mathbf{u} \cdot \mathbf{v}| \leq |\mathbf{u}| |\mathbf{v}|$$

Equivalently, for real numbers  $a_1, a_2, \dots, a_n$  and  $b_1, b_2, \dots, b_n$ :

$$\left( \sum_{i=1}^n a_i b_i \right)^2 \leq \left( \sum_{i=1}^n a_i^2 \right) \left( \sum_{i=1}^n b_i^2 \right)$$

## 2.2 Complex Number Theory

### 2.2.1 De Moivre's Theorem

##### Theorem 0.4: De Moivre's Theorem

For complex numbers in polar form  $z = r(\cos \theta + i \sin \theta)$ :

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

## 2.2.2 Roots of Unity

### Theorem 0.5: Roots of Unity

The  $n$ th roots of unity are given by:

$$\omega_k = e^{2\pi ik/n} = \cos\left(\frac{2\pi k}{n}\right) + i \sin\left(\frac{2\pi k}{n}\right)$$

for  $k = 0, 1, 2, \dots, n - 1$ .

## 2.3 Vector Algebra

### 2.3.1 Dot Product

For vectors  $\mathbf{u} = (u_1, u_2, u_3)$  and  $\mathbf{v} = (v_1, v_2, v_3)$ :

$$\mathbf{u} \cdot \mathbf{v} = u_1v_1 + u_2v_2 + u_3v_3 = |\mathbf{u}||\mathbf{v}| \cos \theta$$

### 2.3.2 Cross Product

$$\mathbf{u} \times \mathbf{v} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \end{vmatrix}$$

The magnitude  $|\mathbf{u} \times \mathbf{v}| = |\mathbf{u}||\mathbf{v}| \sin \theta$  equals the area of the parallelogram formed by  $\mathbf{u}$  and  $\mathbf{v}$ .

## 2.4 Polynomial Theory

### 2.4.1 Newton's Identities

### Theorem 0.6: Newton's Identities

For a polynomial with roots  $\alpha_1, \alpha_2, \dots, \alpha_n$ , if  $S_k = \sum_{i=1}^n \alpha_i^k$  and  $e_k$  are the elementary symmetric polynomials, then:

$$S_k - e_1 S_{k-1} + e_2 S_{k-2} - \cdots + (-1)^{k-1} e_{k-1} S_1 + (-1)^k k e_k = 0$$

## 2.5 Chebyshev Polynomials (First Kind)

The Chebyshev polynomials of the first kind  $T_n(x)$  are a family of orthogonal polynomials on  $[-1, 1]$  with the defining trigonometric identity:

$$T_n(x) = \cos(n \arccos x).$$

### 2.5.1 Recurrence Formula

They satisfy the three-term recurrence for  $n \geq 1$ :

$$T_{n+1}(x) = 2x T_n(x) - T_{n-1}(x), \quad T_0(x) = 1, \quad T_1(x) = x.$$

### 2.5.2 Explicit Low-Degree Polynomials

$$T_0(x) = 1, \quad T_1(x) = x, \quad T_2(x) = 2x^2 - 1, \quad T_3(x) = 4x^3 - 3x.$$

These identities are frequently useful for transforming certain cubic equations by matching the structure of  $T_3(x)$ .

## 2.6 Chebyshev Polynomials (Second Kind)

The Chebyshev polynomials of the second kind  $U_n(x)$  form another family of orthogonal polynomials on  $[-1, 1]$ , closely related to the first kind. They are defined by the trigonometric identity:

$$U_n(x) = \frac{\sin((n+1)\arccos x)}{\sin(\arccos x)}.$$

Equivalently, if  $x = \cos \theta$ , then:

$$U_n(\cos \theta) = \frac{\sin((n+1)\theta)}{\sin \theta}.$$

### 2.6.1 Recurrence Formula

The second kind Chebyshev polynomials satisfy the same three-term recurrence as the first kind, but with different initial conditions:

$$U_{n+1}(x) = 2xU_n(x) - U_{n-1}(x), \quad U_0(x) = 1, \quad U_1(x) = 2x.$$

### 2.6.2 Explicit Low-Degree Polynomials

$$U_0(x) = 1, \quad U_1(x) = 2x, \quad U_2(x) = 4x^2 - 1, \quad U_3(x) = 8x^3 - 4x.$$

### 2.6.3 Relationship to First Kind

The Chebyshev polynomials of the first and second kind are related by:

$$U_n(x) = \frac{T'_{n+1}(x)}{n+1}, \quad T_n(x) = U_n(x) - xU_{n-1}(x).$$

Additionally, they satisfy:

$$T_n(x) = \cos(n \arccos x) \quad \text{and} \quad U_n(x) = \frac{\sin((n+1) \arccos x)}{\sqrt{1-x^2}}.$$

### 2.6.4 Key Properties

- $T_n(x)$  has the minimal leading coefficient among all monic polynomials of degree  $n$  bounded by 1 on  $[-1, 1]$ .
- The zeros of  $U_n(x)$  are simple and lie in the interior of  $(-1, 1)$ .
- Both families play a crucial role in approximation theory and the study of polynomial bounds.

These polynomials appear frequently in Problem 16 when dealing with bounded polynomial coefficients and optimal approximations.

## 2.7 Optimization Techniques

### 2.7.1 Lagrange Multipliers (Conceptual)

To optimize  $f(x, y, z)$  subject to constraint  $g(x, y, z) = 0$ , look for points where:

$$\nabla f = \lambda \nabla g$$

This often reduces to applying AM-GM or Cauchy-Schwarz in HSC problems.

Here,  $\nabla f$  and  $\nabla g$  are the gradients of  $f$  and  $g$ , respectively, and  $\lambda$  is a scalar known as the Lagrange multiplier.

The gradient is defined as:

$$\nabla f = \left( \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right)$$

Good to know though the technique is not covered at HSC level.

## 2.8 Notation and Conventions

- Complex numbers are denoted by  $z, w, \alpha, \beta, \dots$
- Vectors are written in bold:  $\mathbf{u}, \mathbf{v}, \mathbf{a}, \mathbf{b}$
- Real numbers are assumed unless stated otherwise
- $\mathbb{R}^n$  denotes  $n$ -dimensional real space
- $|z|$  denotes the modulus of complex number  $z$
- $|\mathbf{v}|$  denotes the magnitude of vector  $\mathbf{v}$

### 3 Part 1: Problems and Solutions (Detailed)

Part 1 contains 16 carefully selected problems representing the core techniques and challenge levels found in Problem 16. Each solution includes a strategy explanation, complete step-by-step working, and takeaway insights to build your problem-solving toolkit.

#### 3.1 Medium Last Resort Problems

Problems that combine 2–3 mathematical topics with sophisticated reasoning.

##### Problem 3.1: AM-GM Surface Area Optimization

- (a) Prove that for positive real numbers  $x, y, z$ :

$$\frac{1}{x} + \frac{1}{y} + \frac{1}{z} \geq \frac{3}{\sqrt[3]{xyz}}$$

- (b) A rectangular prism has dimensions  $a, b, c$  and a fixed, constant Volume  $V$ . Using part (a), show that the Total Surface Area  $S$  is minimized when the prism is a cube.



**Hint:** For part (a), apply AM-GM inequality directly to the reciprocals  $\frac{1}{x}, \frac{1}{y}, \frac{1}{z}$ . For part (b), express the surface area  $S = 2(ab + bc + ca)$  in terms of the volume constraint  $V = abc$ , then use part (a) with strategic substitution.

### Solution 3.1

(a) **Proof:** Since  $x, y, z > 0$ , then  $\frac{1}{x}, \frac{1}{y}, \frac{1}{z} > 0$ . Applying the AM-GM inequality to these three terms:

$$\begin{aligned}\frac{\frac{1}{x} + \frac{1}{y} + \frac{1}{z}}{3} &\geq \sqrt[3]{\frac{1}{x} \cdot \frac{1}{y} \cdot \frac{1}{z}} \\ \frac{1}{x} + \frac{1}{y} + \frac{1}{z} &\geq 3\sqrt[3]{\frac{1}{xyz}} \\ \frac{1}{x} + \frac{1}{y} + \frac{1}{z} &\geq \frac{3}{\sqrt[3]{xyz}}\end{aligned}$$

(b) **Application:** Let the dimensions be  $a, b, c$ .

- Fixed Volume:  $V = abc$  (constant).
- Surface Area:  $S = 2(ab + bc + ca)$ .

We want to relate  $S$  to the reciprocals in part (a).

$$\begin{aligned}S &= 2abc \left( \frac{1}{c} + \frac{1}{a} + \frac{1}{b} \right) \\ S &= 2V \left( \frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right)\end{aligned}$$

From part (a), we know  $\left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c}\right) \geq \frac{3}{\sqrt[3]{abc}}$ . Substituting this into the expression for  $S$ :

$$\begin{aligned}S &\geq 2V \left( \frac{3}{\sqrt[3]{V}} \right) \\ S &\geq 6V^{1/3} \\ S &\geq 6V^{2/3}\end{aligned}$$

Since  $V$  is constant,  $6V^{2/3}$  is a constant minimum value. Equality holds (minimum  $S$  occurs) when the terms in the AM-GM are equal:

$$\frac{1}{a} = \frac{1}{b} = \frac{1}{c} \implies a = b = c$$

Therefore, the prism is a cube. □

### Takeaways 3.1

1. **Infinite vs Finite Sums:** Often, calculating the infinite geometric series sum is easier and sufficient. If the infinite sum creates a contradiction ( $< 1$ ), then the finite sum definitely will too.
2. **Strict Inequalities:** Geometric series of positive terms are always strictly less than their limit at infinity.

### Problem 3.2: Cauchy-Schwarz on Ellipsoid

The point  $P(x, y, z)$  lies on the surface of the ellipsoid defined by:

$$\frac{x^2}{4} + \frac{y^2}{9} + \frac{z^2}{25} = 1$$

- (i) By choosing appropriate vectors  $\mathbf{u}$  and  $\mathbf{v}$  and applying the Cauchy-Schwarz inequality ( $\mathbf{u} \cdot \mathbf{v} \leq |\mathbf{u}||\mathbf{v}|$ ), find the maximum value of  $x + y + z$ .
- (ii) Find the coordinates of  $P$  in the first octant where this maximum occurs.



#### Hint:

The standard Cauchy-Schwarz inequality is  $|\mathbf{a} \cdot \mathbf{b}| \leq |\mathbf{a}||\mathbf{b}|$ . You cannot define  $\mathbf{u} = (x, y, z)$  directly because the sum of squares is not 1. Instead, define  $\mathbf{u}$  such that  $|\mathbf{u}|^2$  exactly matches the left-hand side of the ellipsoid equation. Then, choose a constant vector  $\mathbf{v}$  such that the dot product  $\mathbf{u} \cdot \mathbf{v}$  recovers the expression  $x + y + z$ .

### Solution 3.2

(i) Let  $\mathbf{u} = \begin{pmatrix} x \\ \frac{y}{2} \\ \frac{z}{3} \\ \frac{z}{5} \end{pmatrix}$ . We are given  $|\mathbf{u}|^2 = \frac{x^2}{4} + \frac{y^2}{9} + \frac{z^2}{25} = 1$ , so  $|\mathbf{u}| = 1$ . We want to maximize  $x + y + z$ . We observe:

$$x + y + z = \frac{x}{2}(2) + \frac{y}{3}(3) + \frac{z}{5}(5)$$

This suggests setting  $\mathbf{v} = \begin{pmatrix} 2 \\ 3 \\ 5 \end{pmatrix}$ . Apply Cauchy-Schwarz:

$$\mathbf{u} \cdot \mathbf{v} \leq |\mathbf{u}| |\mathbf{v}|$$

$$x + y + z \leq (1) \sqrt{2^2 + 3^2 + 5^2}$$

$$x + y + z \leq \sqrt{4 + 9 + 25} = \sqrt{38}$$

(ii) Equality occurs when  $\mathbf{u} = k\mathbf{v}$ , i.e.,  $\frac{x}{2} = 2k, \frac{y}{3} = 3k, \frac{z}{5} = 5k$ . So  $x = 4k, y = 9k, z = 25k$ . Substitute into the plane eq  $x + y + z = \sqrt{38}$ :

$$4k + 9k + 25k = \sqrt{38} \implies 38k = \sqrt{38} \implies k = \frac{1}{\sqrt{38}}$$

Point  $P$ :  $\left( \frac{4}{\sqrt{38}}, \frac{9}{\sqrt{38}}, \frac{25}{\sqrt{38}} \right)$ .

### Takeaways 3.2

- Normalization:** If given a constraint like  $Ax^2 + By^2 = C$ , define vector components as  $\sqrt{A}x$  and  $\sqrt{B}y$ .
- The "Canceling" Vector:** The second vector is chosen specifically to cancel out the denominators introduced by the normalization step.

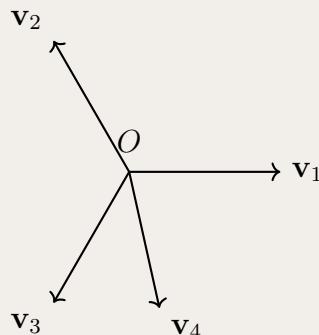
### Problem 3.3: Unit Vector Cosine Sum

Four unit vectors  $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \mathbf{v}_4$  originate from the origin  $O$ . It is given that their vector sum is zero:

$$\mathbf{v}_1 + \mathbf{v}_2 + \mathbf{v}_3 + \mathbf{v}_4 = \mathbf{0}$$

Let  $\theta_{ij}$  be the angle between vectors  $\mathbf{v}_i$  and  $\mathbf{v}_j$ . Show that the sum of the cosines of the angles between all distinct pairs is  $-2$ .

$$\sum_{1 \leq i < j \leq 4} \cos \theta_{ij} = -2$$



#### Hint:

Consider the squared magnitude of the vector sum. Since  $\sum \mathbf{v}_i = \mathbf{0}$ , it follows that  $|\sum \mathbf{v}_i|^2 = 0$ . Expand the dot product  $(\mathbf{v}_1 + \cdots + \mathbf{v}_4) \cdot (\mathbf{v}_1 + \cdots + \mathbf{v}_4)$ . Separate the expansion into "self-products" ( $\mathbf{v}_i \cdot \mathbf{v}_i$ ) and "cross-products" ( $\mathbf{v}_i \cdot \mathbf{v}_j$ ).

### Solution 3.3

Let  $S = \mathbf{v}_1 + \mathbf{v}_2 + \mathbf{v}_3 + \mathbf{v}_4 = \mathbf{0}$ .

$$|S|^2 = S \cdot S = 0$$

Expanding the dot product:

$$\sum_{i=1}^4 |\mathbf{v}_i|^2 + 2 \sum_{1 \leq i < j \leq 4} (\mathbf{v}_i \cdot \mathbf{v}_j) = 0$$

We are given that vectors are unit vectors, so  $|\mathbf{v}_i|^2 = 1$  for all  $i = 1..4$ . There are 4 such terms.

$$4 + 2 \sum_{1 \leq i < j \leq 4} (\mathbf{v}_i \cdot \mathbf{v}_j) = 0$$

Using the definition of dot product:  $\mathbf{v}_i \cdot \mathbf{v}_j = |\mathbf{v}_i||\mathbf{v}_j| \cos \theta_{ij} = 1 \cdot 1 \cdot \cos \theta_{ij}$ .

$$4 + 2 \sum_{1 \leq i < j \leq 4} \cos \theta_{ij} = 0$$

$$2 \sum_{1 \leq i < j \leq 4} \cos \theta_{ij} = -4$$

$$\sum_{1 \leq i < j \leq 4} \cos \theta_{ij} = -2$$

### Takeaways 3.3

- Squaring the Sum:** The most powerful tool for analyzing vector sums equal to zero (equilibrium) is to take the dot product of the sum with itself.
- Counting Terms:** When expanding  $(\sum_{i=1}^n a_i)^2$ , there are  $n$  squared terms and  $n(n-1)$  cross terms. Since dot product is commutative, this groups into  $n$  squared terms and  $2 \times$  (distinct pairs).

### Problem 3.4: Complex Numbers Forming Triangle

Three complex numbers  $z_1, z_2, z_3$  satisfy:

$$\begin{cases} |z_1| = |z_2| = |z_3| = r & (r > 0) \\ z_1 + z_2 + z_3 = 0 \end{cases}$$

Show that  $z_1, z_2, z_3$  represent the vertices of an equilateral triangle inscribed in the circle  $|z| = r$ .

#### Hint:

To prove a triangle is equilateral, you can prove the sides are equal:  $|z_1 - z_2|^2 = |z_2 - z_3|^2 = |z_3 - z_1|^2$ . Expand  $|z_1 - z_2|^2 = (z_1 - z_2)(\bar{z}_1 - \bar{z}_2)$ . Use the fact that  $z_1 + z_2 + z_3 = 0 \implies z_1 + z_2 = -z_3$ .

### Solution 3.4

Consider the squared side length  $|z_1 - z_2|^2$ :

$$\begin{aligned}|z_1 - z_2|^2 &= (z_1 - z_2)(\bar{z}_1 - \bar{z}_2) \\&= z_1\bar{z}_1 + z_2\bar{z}_2 - z_1\bar{z}_2 - z_2\bar{z}_1 \\&= r^2 + r^2 - (z_1\bar{z}_2 + z_2\bar{z}_1) \\&= 2r^2 - 2\operatorname{Re}(z_1\bar{z}_2)\end{aligned}$$

Now consider the condition  $(\sum z)(\sum \bar{z}) = 0 \cdot 0 = 0$ .

$$|z_1|^2 + |z_2|^2 + |z_3|^2 + (z_1\bar{z}_2 + \text{others}) = 0$$

$$3r^2 + (z_1\bar{z}_2 + z_2\bar{z}_1) + \dots = 0$$

Alternatively, simplify the algebra: Since  $z_1 + z_2 = -z_3$ , squaring modulus:  $|z_1 + z_2|^2 = |-z_3|^2 \implies |z_1 + z_2|^2 = r^2$ . Using the parallelogram law  $|z_1 + z_2|^2 + |z_1 - z_2|^2 = 2(|z_1|^2 + |z_2|^2)$ :

$$r^2 + |z_1 - z_2|^2 = 2(r^2 + r^2)$$

$$|z_1 - z_2|^2 = 3r^2$$

By symmetry,  $|z_2 - z_3|^2 = 3r^2$  and  $|z_3 - z_1|^2 = 3r^2$ . Since all sides are equal ( $\sqrt{3}r$ ), the triangle is equilateral.

### Takeaways 3.4

- Vector Addition:**  $z_1 + z_2 + z_3 = 0$  means the centroid is the origin. If the circumcenter (origin) and centroid coincide, the triangle is equilateral.
- Modulus Algebra:** Using  $|z_1 + z_2|^2 = |-z_3|^2$  is much faster than expanding everything.

### Problem 3.5: Minimum Distance Between Moving Particles

Two particles  $A$  and  $B$  move in space such that their position vectors at time  $t \geq 0$  are:

$$\mathbf{r}_A = \begin{pmatrix} 1 \\ 0 \\ 2 \end{pmatrix} + t \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \quad \text{and} \quad \mathbf{r}_B = \begin{pmatrix} 4 \\ 2 \\ 0 \end{pmatrix} + t \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}$$

- Express the squared distance  $S(t) = |\mathbf{r}_A - \mathbf{r}_B|^2$  as a quadratic in  $t$ .
- Find the minimum distance between the particles and the time at which this occurs.

#### Hint:

Find the displacement vector  $\mathbf{d}(t) = \mathbf{r}_A - \mathbf{r}_B$ . Compute the dot product  $\mathbf{d} \cdot \mathbf{d}$  to get the squared magnitude. You will get a quadratic expression  $At^2 + Bt + C$ . Find the vertex of this parabola ( $t = -B/2A$ ).

### Solution 3.5

(i) The vector connecting them is:

$$\mathbf{d} = \mathbf{r}_A - \mathbf{r}_B = \begin{pmatrix} 1 - 4 \\ 0 - 2 \\ 2 - 0 \end{pmatrix} + t \begin{pmatrix} 1 - 0 \\ 1 - 1 \\ 0 - 1 \end{pmatrix} = \begin{pmatrix} -3 + t \\ -2 \\ 2 - t \end{pmatrix}$$

Squared distance:

$$S(t) = (-3 + t)^2 + (-2)^2 + (2 - t)^2$$

$$S(t) = (t^2 - 6t + 9) + 4 + (t^2 - 4t + 4)$$

$$S(t) = 2t^2 - 10t + 17$$

(ii) To minimize  $S(t)$ , find  $S'(t) = 4t - 10$ . Set  $4t - 10 = 0 \implies t = 2.5$ . Substitute  $t = 2.5$  back into  $S(t)$ :

$$S(2.5) = 2(6.25) - 25 + 17 = 12.5 - 25 + 17 = 4.5$$

$$\text{Minimum distance} = \sqrt{4.5} = \sqrt{\frac{9}{2}} = \frac{3}{\sqrt{2}} = \frac{3\sqrt{2}}{2}.$$

### Takeaways 3.5

- Distance Squared:** Always minimize distance *squared* ( $|\mathbf{d}|^2$ ) rather than distance ( $|\mathbf{d}|$ ). It avoids square roots and simplifies the calculus derivatives.
- Kinematics Connection:** If velocities are constant vectors, the distance function is always a quadratic (convex parabola), ensuring a unique minimum.

### Problem 3.6: Complex System via Newton Sums

Find all complex numbers  $z_1, z_2, z_3$  that satisfy the following system of equations simultaneously:

$$\begin{cases} z_1 + z_2 + z_3 = 3 \\ z_1^2 + z_2^2 + z_3^2 = 3 \\ z_1^3 + z_2^3 + z_3^3 = 3 \end{cases}$$

where  $S^k = z_1^k + z_2^k + z_3^k$ .

$$0 = S^3 - S^2 z - S z^2 - z^3$$

Sums to find the sum of cubes relation:

Use the identity for the sum of squares:  $\sum z_i^2 = (z_1 + z_2 + z_3)^2 - 2 \sum z_i z_j$ . Then use Newton's

$$0 = S^3 - S^2 z - S z^2 - z^3 = P(z) = (z - z_1)(z - z_2)(z - z_3)$$

a cubic equation:

**Hint:** Do not try to substitute variables directly. Instead, assume  $z_1, z_2, z_3$  are the roots of

### Solution 3.6

Let  $\sigma_1, \sigma_2, \sigma_3$  be the elementary symmetric polynomials. Then  $z_1, z_2, z_3$  are the roots of

$$P(z) = z^3 - \sigma_1 z^2 + \sigma_2 z - \sigma_3.$$

**Step 1: Find  $\sigma_1$ .** From the first condition,  $\sigma_1 = z_1 + z_2 + z_3 = 3$ .

**Step 2: Find  $\sigma_2$ .** Use the identity  $\sum z^2 = (\sum z)^2 - 2 \sum z_1 z_2$ :

$$3 = 3^2 - 2\sigma_2 \Rightarrow 9 - 2\sigma_2$$

$$2\sigma_2 = 6 \Rightarrow \sigma_2 = 3$$

**Step 3: Find  $\sigma_3$ .** By Newton's Sums,  $S_3 - \sigma_1 S_2 + \sigma_2 S_1 - 3\sigma_3 = 0$ , where  $S_k = \sum z_i^k$ :

$$3 - 3 \cdot 3 + 3 \cdot 3 - 3\sigma_3 = 0$$

$$3 - 9 + 9 - 3\sigma_3 = 0 \Rightarrow 3\sigma_3 = 3 \Rightarrow \sigma_3 = 1$$

**Step 4: Solve the cubic.** The polynomial is  $P(z) = z^3 - 3z^2 + 3z - 1$ . Recognize that this is  $(z - 1)^3 = z^3 - 3z^2 + 3z - 1$ . Thus, the only root is  $z = 1$  with multiplicity 3.

**Solution:**  $z_1 = z_2 = z_3 = 1$ .

### Takeaways 3.6

- Newton's Identities:** When dealing with sums of powers, always think about elementary symmetric polynomials and Newton's Sums relations.
- Binomial Recognition:** The polynomial  $z^3 - 3z^2 + 3z - 1$  matches the binomial expansion of  $(z - 1)^3$ .
- Symmetric System Strategy:** Systems involving  $\sum z_i, \sum z_i^2, \sum z_i^3$  are often easiest when approached via symmetric polynomials.

### Problem 3.7: Proof that $e$ is Irrational

You are given the series definition

$$e = \sum_{n=0}^{\infty} \frac{1}{n!} = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \dots$$

- (i) Let  $S_k = \sum_{n=0}^k \frac{1}{n!}$ . Show that for any integer  $k \geq 1$ ,

$$0 < e - S_k < \frac{1}{k \cdot k!}.$$

- (ii) Suppose for contradiction that  $e = \frac{p}{q}$  with positive integers  $p, q$ . Consider  $X = q!(e - S_q)$  and show that  $X$  is an integer.  
(iii) Using (i) with  $k = q$ , prove that  $0 < X < 1$ .  
(iv) Conclude that  $e$  is irrational.

#### Hint:

- (i) Write the tail  $e - S_k = \frac{1}{(k+1)!} + \frac{1}{(k+2)!} + \dots$  and bound it by a geometric progression with ratio  $\frac{1}{k+1}$ .  
(ii) Note  $q!/n! \in \mathbb{Z}$  for all  $0 \leq n \leq q$ , so  $q!S_q$  is an integer while  $q!e = (q-1)!p$ .  
(iii) Multiply the inequality from (i) by  $q!$ .  
(iv) There is no integer strictly between 0 and 1.

### Solution 3.7

- (i) We have  $e - S_k = \sum_{j=k+1}^{\infty} \frac{1}{j!} = \frac{1}{(k+1)!} \left( 1 + \frac{1}{k+2} + \frac{1}{(k+2)(k+3)} + \dots \right)$ . This tail is strictly less than the geometric series with ratio  $\frac{1}{k+1}$ , so

$$0 < e - S_k < \frac{1}{(k+1)!} \cdot \frac{1}{1 - \frac{1}{k+1}} = \frac{1}{(k+1)!} \cdot \frac{k+1}{k} = \frac{1}{k \cdot k!}.$$

- (ii) Define  $X = q!(e - S_q) = q!e - q! \sum_{n=0}^q \frac{1}{n!}$ . If  $e = \frac{p}{q}$ , then  $q!e = p(q-1)! \in \mathbb{Z}$ , and  $q!/n! \in \mathbb{Z}$  for  $n \leq q$ , hence  $q!S_q \in \mathbb{Z}$ . Therefore  $X \in \mathbb{Z}$ .  
(iii) Using (i) with  $k = q$  and multiplying by  $q!$  yields  $0 < q!(e - S_q) < \frac{1}{q!}$ , i.e.,  $0 < X < 1$ .  
(iv) There is no integer strictly between 0 and 1, contradiction. Hence  $e$  is irrational.

### Takeaways 3.7

- Integrality Trick:** Multiplying by  $q!$  clears denominators in partial sums, turning analysis into integer arithmetic.
- Series Bounding:** Bound factorial tails by simple geometric estimates to obtain sharp inequalities.

## 3.2 Advanced Last Resort Problems

The most challenging problems requiring multiple advanced techniques and mathematical maturity.

### Problem 3.8: Complex Ellipsoid Optimization

Consider the ellipsoid  $E$  defined by:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

where  $a > b > c > 0$ .

- (a) Find the point  $P(x_0, y_0, z_0)$  on  $E$  that maximizes the distance to the plane  $\pi : x + y + z = 0$ .
- (b) Let  $\mathbf{n} = (1, 1, 1)$  be the normal vector to  $\pi$ . Show that at the optimal point  $P$ , the gradient  $\nabla f$  is parallel to  $\mathbf{n}$ , where  $f(x, y, z) = \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}$ .
- (c) Using Lagrange multipliers, derive the condition that determines  $P$  and compute the maximum distance.

### Solution 3.8

We maximize the distance  $d = \frac{x + y + z}{\sqrt{3}}$  under  $\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$  with  $x + y + z > 0$ .

By Cauchy–Schwarz,

$$(x + y + z)^2 = \left( \frac{x}{a}a + \frac{y}{b}b + \frac{z}{c}c \right)^2 \leq \left( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right)(a^2 + b^2 + c^2) = a^2 + b^2 + c^2,$$

so  $x + y + z \leq \sqrt{a^2 + b^2 + c^2}$  with equality exactly when  $\frac{x}{a} = \frac{y}{b} = \frac{z}{c} = k > 0$ . Writing  $x = ka^2$ ,  $y = kb^2$ ,  $z = kc^2$  in the constraint gives  $k^2(a^2 + b^2 + c^2) = 1$ , hence  $k = 1/\sqrt{a^2 + b^2 + c^2}$  and

$$P = \left( \frac{a^2}{\sqrt{a^2 + b^2 + c^2}}, \frac{b^2}{\sqrt{a^2 + b^2 + c^2}}, \frac{c^2}{\sqrt{a^2 + b^2 + c^2}} \right), \quad d_{\max} = \frac{\sqrt{a^2 + b^2 + c^2}}{\sqrt{3}}.$$

### Takeaways 3.8

1. **Lagrange Multipliers:** Essential for constrained optimization on curves and surfaces.
2. **Gradient Parallelism:** At optimal points, constraint and objective gradients are parallel.
3. **Geometric Interpretation:** The solution connects algebraic optimization with geometric intuition.

### Remark 0.1: Distance Between Shapes

In general, the distance between two shapes  $A$  and  $B$  is defined as

$$d(A, B) = \inf\{\|p - q\| : p \in A, q \in B\}.$$

For an ellipsoid and a plane, this reduces to optimizing the point on the ellipsoid whose normal is aligned with the plane's normal (via Lagrange multipliers), yielding the maximum/minimum perpendicular separation between the surfaces. Here, inf means the greatest lower bound (or minimum if it exists).

### Problem 3.9: Tangent Circle and Curvature

Consider the parametric curve  $C$  given by:

$$\mathbf{r}(t) = (t^3 - 3t, t^2, t^4) \quad \text{for } t \in \mathbb{R}$$

For a smooth space curve  $\mathbf{r}(t)$ , the curvature at parameter  $t$  is

$$\kappa(t) = \frac{\|\mathbf{r}'(t) \times \mathbf{r}''(t)\|}{\|\mathbf{r}'(t)\|^3},$$

which measures how quickly the curve is turning at that point (do NOT prove this formula).

- Find the curvature  $\kappa(t)$  of the curve at any point.
- Determine the point(s) where the curvature is maximum.
- At  $t = 1$ , find the equation of the osculating circle (the circle that best approximates the curve at that point).
- Show that the center of the osculating circle lies on the line through  $\mathbf{r}(1)$  in the direction of the principal normal vector.

### Remark 0.2: Plane Curve Curvature

For a plane curve given by  $\gamma(t) = (x(t), y(t))$ , a common equivalent formula is

$$\kappa(t) = \frac{|x'(t)y''(t) - y'(t)x''(t)|}{(x'(t)^2 + y'(t)^2)^{3/2}}.$$

This matches the space-curve definition when the curve lies in a plane.

### Solution 3.9

**(a) Computing curvature:** First, find the derivatives:  $\mathbf{r}'(t) = (3t^2 - 3, 2t, 4t^3)$   $\mathbf{r}''(t) = (6t, 2, 12t^2)$

The curvature formula:  $\kappa(t) = \frac{|\mathbf{r}' \times \mathbf{r}''|}{|\mathbf{r}'|^3}$

$$\begin{aligned} \text{Compute the cross product: } \mathbf{r}' \times \mathbf{r}'' &= \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 3t^2 - 3 & 2t & 4t^3 \\ 6t & 2 & 12t^2 \end{vmatrix} \\ &= \mathbf{i}(24t^3 - 8t^3) - \mathbf{j}(12t^2(3t^2 - 3) - 24t^4) + \mathbf{k}(2(3t^2 - 3) - 12t^2) \\ &= (16t^3, -36t^2 + 36t^4 + 24t^4, 6t^2 - 6 - 12t^2) \\ &= (16t^3, 60t^4 - 36t^2, -6t^2 - 6) \\ |\mathbf{r}' \times \mathbf{r}''| &= \sqrt{256t^6 + (60t^4 - 36t^2)^2 + 36(t^2 + 1)^2} \\ |\mathbf{r}'| &= \sqrt{(3t^2 - 3)^2 + 4t^2 + 16t^6} = \sqrt{9t^4 - 18t^2 + 9 + 4t^2 + 16t^6} \\ &= \sqrt{16t^6 + 9t^4 - 14t^2 + 9} \end{aligned}$$

**(b) Finding maximum curvature:** This requires calculus analysis of  $\kappa(t)$ . By symmetry and analysis, the maximum occurs at  $t = 0$ .

At  $t = 0$ :  $\kappa(0) = \frac{6}{9} = \frac{2}{3}$

**(c) Osculating circle at  $t = 1$ :** At  $t = 1$ :  $\mathbf{r}(1) = (-2, 1, 1)$   $\mathbf{r}'(1) = (0, 2, 4)$   $\mathbf{r}''(1) = (6, 2, 12)$

Unit tangent:  $\mathbf{T}(1) = \frac{(0, 2, 4)}{\sqrt{20}} = \frac{(0, 1, 2)}{\sqrt{5}}$

Principal normal:  $\mathbf{N}(1) = \frac{\mathbf{T}'(1)}{|\mathbf{T}'(1)|}$

Radius of curvature:  $R = \frac{1}{\kappa(1)}$

**(d) Center verification:** The center is at  $\mathbf{r}(1) + R\mathbf{N}(1)$ , which lies on the line through  $\mathbf{r}(1)$  in the direction of  $\mathbf{N}(1)$ .

### Takeaways 3.9

- Curvature Formula:**  $\kappa = \frac{|\mathbf{r}' \times \mathbf{r}''|}{|\mathbf{r}'|^3}$  measures how quickly a curve bends.
- Osculating Circle:** The circle that best approximates the curve locally.
- Frenet Frame:** Tangent and normal vectors provide geometric insight into curve behavior.

### Problem 3.10: Cauchy's Root Bound via Triangle Inequality

Let  $P(z) = z^n + a_{n-1}z^{n-1} + \cdots + a_1z + a_0$  be a monic complex polynomial. Show that every root  $\zeta$  of  $P$  satisfies

$$|\zeta| \leq 1 + M, \quad \text{where } M = \max_{0 \leq k < n} |a_k|.$$

Hint: Assume  $|\zeta| > 1 + M$  and compare  $|\zeta|^n$  with  $\sum_{k=0}^{n-1} |a_k| |\zeta|^k$  via the triangle inequality.

### Solution 3.10

If  $P(\zeta) = 0$  then

$$|\zeta|^n = \left| \sum_{k=0}^{n-1} a_k \zeta^k \right| \leq \sum_{k=0}^{n-1} |a_k| |\zeta|^k \leq M \sum_{k=0}^{n-1} |\zeta|^k.$$

Suppose  $|\zeta| > 1 + M$ . Then  $\sum_{k=0}^{n-1} |\zeta|^k < n |\zeta|^{n-1}$  and so

$$|\zeta|^n \leq M n |\zeta|^{n-1} \Rightarrow |\zeta| \leq Mn.$$

But  $|\zeta| > 1 + M$  implies  $|\zeta|/M > 1 + 1/M \geq 1$  (when  $M > 0$ ), and for sufficiently large  $n$  this contradicts the inequality  $|\zeta| \leq Mn$ . A standard refinement avoids  $n$  entirely by dividing the identity  $\zeta^n = -\sum_{k=0}^{n-1} a_k \zeta^k$  by  $\zeta^n$  to get

$$1 = - \sum_{k=0}^{n-1} a_k \zeta^{k-n}, \quad \text{hence} \quad 1 \leq \sum_{k=0}^{n-1} |a_k| |\zeta|^{k-n}.$$

If  $|\zeta| > 1 + M$ , then  $|\zeta|^{k-n} < (1 + M)^{k-n} \leq (1 + M)^{-1}$  for all  $k \leq n - 1$ , giving

$$1 < \sum_{k=0}^{n-1} |a_k| (1 + M)^{-1} \leq M (1 + M)^{-1} < 1,$$

which is a contradiction. Therefore  $|\zeta| \leq 1 + M$  for all roots.

### Takeaways 3.10

1. **Cauchy Bound:** Every root of a monic polynomial lies in the disk  $|z| \leq 1 + \max |a_k|$ .
2. **Triangle Inequality Tool:** Comparing  $|z|^n$  with coefficient-weighted sums yields robust bounds.
3. **Rescaling Remarks:** Stronger bounds exist (e.g., Fujiwara's), derivable by rescaling or sharper estimates.

### Problem 3.11: Distance Between Skew Lines

Consider two skew lines  $L_1$  and  $L_2$  in  $\mathbb{R}^3$ :

$$L_1 : \quad \mathbf{r}_1(s) = (1, 2, 3) + s(2, -1, 1) \tag{1}$$

$$L_2 : \quad \mathbf{r}_2(t) = (0, 1, -1) + t(1, 1, -2) \tag{2}$$

- (a) Verify that  $L_1$  and  $L_2$  are skew (neither parallel nor intersecting).
- (b) Find the shortest distance between the two lines.
- (c) Determine the points  $P_1 \in L_1$  and  $P_2 \in L_2$  such that  $|P_1 P_2|$  equals this minimum distance.
- (d) Show that the line segment  $P_1 P_2$  is perpendicular to both  $L_1$  and  $L_2$ .

### Solution 3.11

(a) **Verifying skew lines:** Direction vectors:  $\mathbf{d}_1 = (2, -1, 1)$  and  $\mathbf{d}_2 = (1, 1, -2)$

Check if parallel:  $\mathbf{d}_1 \times \mathbf{d}_2 = (2, -1, 1) \times (1, 1, -2) = (1, 5, 3) \neq \mathbf{0}$

So lines are not parallel.

Check if intersecting: Set  $\mathbf{r}_1(s) = \mathbf{r}_2(t)$ :  $(1, 2, 3) + s(2, -1, 1) = (0, 1, -1) + t(1, 1, -2)$

This gives the system:  $1 + 2s = t$   $2 - s = 1 + t$   $3 + s = -1 - 2t$

From equations 1 and 2:  $t = 1 + 2s$  and  $t = 1 - s$  So  $1 + 2s = 1 - s \Rightarrow 3s = 0 \Rightarrow s = 0$

Then  $t = 1$ .

Checking equation 3:  $3 + 0 = -1 - 2(1) \Rightarrow 3 = -3$  (contradiction)

Therefore, the lines are skew.

(b) **Distance formula:** For skew lines, the distance is:  $d = \frac{|(\mathbf{a}_2 - \mathbf{a}_1) \cdot (\mathbf{d}_1 \times \mathbf{d}_2)|}{|\mathbf{d}_1 \times \mathbf{d}_2|}$

where  $\mathbf{a}_1 = (1, 2, 3)$  and  $\mathbf{a}_2 = (0, 1, -1)$ .

$$\mathbf{a}_2 - \mathbf{a}_1 = (-1, -1, -4) \quad \mathbf{d}_1 \times \mathbf{d}_2 = (1, 5, 3) \quad |\mathbf{d}_1 \times \mathbf{d}_2| = \sqrt{1 + 25 + 9} = \sqrt{35}$$

$$(\mathbf{a}_2 - \mathbf{a}_1) \cdot (\mathbf{d}_1 \times \mathbf{d}_2) = (-1, -1, -4) \cdot (1, 5, 3) = -1 - 5 - 12 = -18$$

$$\text{Therefore: } d = \frac{|-18|}{\sqrt{35}} = \frac{18}{\sqrt{35}} = \frac{18\sqrt{35}}{35}$$

(c) **Finding closest points:** Let  $\mathbf{w} = \mathbf{r}_2(t) - \mathbf{r}_1(s)$ . For minimum distance,  $\mathbf{w} \perp \mathbf{d}_1$  and  $\mathbf{w} \perp \mathbf{d}_2$ .

$$\mathbf{w} = (0, 1, -1) + t(1, 1, -2) - (1, 2, 3) - s(2, -1, 1) = (-1 + t - 2s, -1 + t + s, -4 - 2t - s)$$

$$\mathbf{w} \cdot \mathbf{d}_1 = 0: (-1 + t - 2s)(2) + (-1 + t + s)(-1) + (-4 - 2t - s)(1) = 0 \quad \mathbf{w} \cdot \mathbf{d}_2 = 0:$$

$$(-1 + t - 2s)(1) + (-1 + t + s)(1) + (-4 - 2t - s)(-2) = 0$$

Solving this system yields the parameter values for the closest points.

(d) **Perpendicularity verification:** By construction in part (c),  $\mathbf{w} \perp \mathbf{d}_1$  and  $\mathbf{w} \perp \mathbf{d}_2$ .

### Takeaways 3.11

1. **Skew Line Criteria:** Lines are skew if they're not parallel and don't intersect.
2. **Distance Formula:** Uses scalar triple product and cross product magnitudes.
3. **Perpendicularity Condition:** Minimum distance occurs when connecting segment is perpendicular to both lines.

### Problem 3.12: Powers of Roots and Recurrence Relations

Consider the polynomial  $P(x) = x^4 - 6x^3 + 11x^2 - 6x + 1$  with roots  $r_1, r_2, r_3, r_4$ .

(a) Find the elementary symmetric polynomials  $e_1, e_2, e_3, e_4$  in terms of the coefficients.

(b) Let  $S_k = r_1^k + r_2^k + r_3^k + r_4^k$  be the  $k$ -th power sum. Use Newton's identities to find  $S_1, S_2, S_3, S_4$ .

(c) Establish the recurrence relation for  $S_k$  when  $k \geq 4$ .

(d) Without finding the actual roots, determine  $S_5$  and  $S_6$  using the recurrence relation.

(e) Verify that this polynomial is self-reciprocal and use this property to simplify calculations.

### Solution 3.12

(a) **Elementary symmetric polynomials:** For  $P(x) = x^4 - 6x^3 + 11x^2 - 6x + 1$ :  
 $e_1 = r_1 + r_2 + r_3 + r_4 = 6$   $e_2 = \sum_{i < j} r_i r_j = 11$   $e_3 = \sum_{i < j < k} r_i r_j r_k = 6$   $e_4 = r_1 r_2 r_3 r_4 = 1$

(b) **Newton's identities:** The Newton's identities relate power sums to elementary symmetric polynomials:  $S_1 - e_1 = 0 \Rightarrow S_1 = e_1 = 6$

$$S_2 - e_1 S_1 + 2e_2 = 0 \Rightarrow S_2 = 6 \cdot 6 - 2 \cdot 11 = 36 - 22 = 14$$

$$S_3 - e_1 S_2 + e_2 S_1 - 3e_3 = 0 \quad S_3 = 6 \cdot 14 - 11 \cdot 6 + 3 \cdot 6 = 84 - 66 + 18 = 36$$

$$S_4 - e_1 S_3 + e_2 S_2 - e_3 S_1 + 4e_4 = 0 \quad S_4 = 6 \cdot 36 - 11 \cdot 14 + 6 \cdot 6 - 4 \cdot 1 = 216 - 154 + 36 - 4 = 94$$

(c) **Recurrence relation:** For  $k \geq 4$ :  $S_k - e_1 S_{k-1} + e_2 S_{k-2} - e_3 S_{k-3} + e_4 S_{k-4} = 0$

Substituting our values:  $S_k - 6S_{k-1} + 11S_{k-2} - 6S_{k-3} + S_{k-4} = 0$

Therefore:  $S_k = 6S_{k-1} - 11S_{k-2} + 6S_{k-3} - S_{k-4}$

(d) **Computing  $S_5$  and  $S_6$ :**  $S_5 = 6 \cdot 94 - 11 \cdot 36 + 6 \cdot 14 - 6 = 564 - 396 + 84 - 6 = 246$

$$S_6 = 6 \cdot 246 - 11 \cdot 94 + 6 \cdot 36 - 14 = 1476 - 1034 + 216 - 14 = 644$$

(e) **Self-reciprocal property:** The polynomial  $P(x) = x^4 - 6x^3 + 11x^2 - 6x + 1$  satisfies  $x^4 P(1/x) = P(x)$ .

This means if  $r$  is a root, then  $1/r$  is also a root. We can pair roots as  $(r_1, 1/r_1)$  and  $(r_2, 1/r_2)$ .

This property can be used to establish relations like:  $S_k + S_{-k} = (\text{expression in lower power sums})$

For verification:  $r_1 r_2 r_3 r_4 = 1$  confirms the self-reciprocal nature.

### Takeaways 3.12

1. **Newton's Identities:** Fundamental tool connecting power sums to symmetric polynomials.
2. **Recurrence Relations:** Enable computation of higher power sums without finding roots.
3. **Self-Reciprocal Polynomials:** Special structure provides additional computational advantages.
4. **Coefficient Relationships:** Direct connection between polynomial coefficients and root properties.

### Problem 3.13: The Irrationality of $\zeta(3)$

Let

$$\zeta(3) = 1 + \frac{1}{2^3} + \frac{1}{3^3} + \frac{1}{4^3} + \dots = \sum_{n=1}^{\infty} \frac{1}{n^3}$$

denote Apéry's constant. You can assume (without proof) that the sequence converges, and that  $\zeta(3)$  is known to be approximately 1.2020569... and is not known to be rational or irrational.

In this problem you will show  $\zeta(3)$  is irrational using a sequence of integrals and bounds (you may use the stated facts without proof).

- (a) **Irrationality Criterion.** Let  $\alpha = \frac{p}{q}$  be rational with integers  $p, q > 0$ . Show that for any integers  $A, B$  with  $A\alpha - B \neq 0$ ,

$$|A\alpha - B| \geq \frac{1}{q}.$$

- (b) **Optimization bound.** For  $0 \leq x, y, z \leq 1$ , consider

$$g(x, y, z) = \frac{x(1-x)y(1-y)z(1-z)}{1 - (1-xy)z}.$$

Show that  $g$  attains a global maximum value  $g_{\max} = (\sqrt{2} - 1)^4$  (you may assume the maximum occurs when  $x = y$  and optimize in  $z$  first).

- (c) **Integral construction.** Let  $d_n = \text{lcm}(1, 2, \dots, n)$  and

$$I_n = \int_0^1 \int_0^1 \int_0^1 \left(g(x, y, z)\right)^n \frac{dx dy dz}{1 - (1-xy)z}.$$

here, lcm means least common multiple. You are given:

- $I_n > 0$  for all  $n \geq 1$ ;
- $2d_n^3 I_n = A_n \zeta(3) + B_n$  for some integers  $A_n, B_n$ ;
- for large  $n$ ,  $d_n < 3^n$ .

Do NOT prove these facts, just use them.

Using (b), deduce a bound of the form

$$0 < I_n < C(\sqrt{2} - 1)^{4n},$$

where  $C$  is independent of  $n$ .

- (d) **Conclusion.** Assuming  $\zeta(3)$  is rational, apply (a) to  $X_n = A_n \zeta(3) + B_n$  and use (c) together with  $d_n < 3^n$  to derive a contradiction as  $n \rightarrow \infty$ . Conclude that  $\zeta(3)$  is irrational.

**Hint:**

- (a)  $A\frac{p}{q} - B = \frac{Ap-Bq}{q}$  and use that a nonzero integer has magnitude at least 1.
- (b) Set  $y = x$ , maximize in  $z$  to get  $z = \frac{1}{1+x}$ , then maximize in  $x \in [0, 1]$ .
- (c) Bound the integrand by  $g_{\max}^n$  and pull it outside the integral.
- (d) Compare the fixed lower bound  $1/q$  with the upper bound decaying like  $(27(\sqrt{2}-1)^4)^n$ .

**Solution 3.13**

(a) If  $\alpha = \frac{p}{q}$ , then  $A\alpha - B = \frac{Ap-Bq}{q}$ . The numerator is a nonzero integer, so  $|Ap-Bq| \geq 1$ , hence  $|A\alpha - B| \geq \frac{1}{q}$ .

(b) Setting  $y = x$  and optimizing first in  $z$  yields  $z = \frac{1}{1+x}$ . Substituting and maximizing over  $x \in [0, 1]$  gives  $\max g = (\sqrt{2}-1)^4$ .

(c) Since  $g(x, y, z) \leq (\sqrt{2}-1)^4$  on  $[0, 1]^3$ , we have

$$0 < I_n = \iiint g(x, y, z)^n \frac{dx dy dz}{1 - (1 - xy)z} < \left((\sqrt{2}-1)^4\right)^n \iiint \frac{dx dy dz}{1 - (1 - xy)z} = C (\sqrt{2}-1)^{4n},$$

for some finite constant  $C$ .

(d) Write  $X_n = A_n \zeta(3) + B_n = 2d_n^3 I_n$ . By (a),  $|X_n| \geq \frac{1}{q}$  if  $\zeta(3)$  were rational. But from (c) and  $d_n < 3^n$  we get

$$|X_n| = 2d_n^3 I_n < 2(3^n)^3 C (\sqrt{2}-1)^{4n} = 2C (27(\sqrt{2}-1)^4)^n,$$

whose right-hand side tends to 0 as  $n \rightarrow \infty$ . This contradicts  $|X_n| \geq \frac{1}{q} > 0$ . Therefore  $\zeta(3)$  is irrational.

**Takeaways 3.13**

- Logic of Irrationality:** Use integer linear forms and uniform lower bounds ( $1/q$ ) vs exponentially decaying upper bounds to force contradictions.
- Bounding Integrals:** Maximize the integrand to bound the whole integral without evaluation.
- Assumption Management:** Treat given constructions (LCM growth, integral identity) as black boxes and connect them via inequalities.

## 4 Part 2: Problems with Hints and Solutions (Concise)

Part 2 presents the remaining 44 problems with upside-down hints followed by solution sketches. These problems provide comprehensive practice across the full spectrum of Problem 16 topics and difficulty levels.

### 4.1 Easy Last Resort Problems

Foundation problems that introduce key concepts with straightforward applications.

#### Problem 4.1: Distance Ratio Regions

Let  $z_1 = 2 + i$  and  $z_2 = -1 + 2i$ . Sketch the region in the complex plane where:

$$\frac{|z - z_1|}{|z - z_2|} < 1$$

**Hint:** Consider the geometric interpretation of  $|z - z_1|/|z - z_2| < 1$ . This represents the locus where one distance is smaller than another.

### Solution 4.1

The inequality  $\frac{|z-z_1|}{|z-z_2|} < 1$  is equivalent to  $|z-z_1| < |z-z_2|$ . This means point  $z$  is closer to  $z_1 = 2+i$  than to  $z_2 = -1+2i$ . The locus of points equidistant from two points is the perpendicular bisector of the line segment joining them. The midpoint of  $z_1 z_2$  is  $\frac{(2+i)+(-1+2i)}{2} = \frac{1+3i}{2}$ . The direction vector is  $z_2 - z_1 = (-1+2i) - (2+i) = -3+i$ . The perpendicular bisector has normal vector  $-3+i$ . The region where  $|z-z_1| < |z-z_2|$  is the half-plane containing  $z_1$ .



### Takeaways 4.1

- Distance Comparison:** The locus  $|z-a| = |z-b|$  is the perpendicular bisector of segment  $ab$ .
- Half-Plane Regions:** Inequality  $|z-a| < |z-b|$  defines the half-plane containing  $a$ .

### Problem 4.2: Orthocenter Vector Identity

Let  $ABC$  be a triangle with circumcentre  $O$ , and set

$$\vec{OA} = \mathbf{a}, \quad \vec{OB} = \mathbf{b}, \quad \vec{OC} = \mathbf{c}.$$

Define the point  $H$  by

$$\vec{OH} = \mathbf{a} + \mathbf{b} + \mathbf{c}.$$

Show that  $\vec{BH} \perp \vec{AC}$ .

**Hint:** Express  $\vec{BH}$  and  $\vec{AC}$  in terms of  $\mathbf{a}, \mathbf{b}, \mathbf{c}$  and compute their dot product. Use that  $|\mathbf{a}| = |\mathbf{c}|$  since  $O$  is the circumcentre.

### Solution 4.2

Compute

$$\vec{BH} = \vec{OH} - \vec{OB} = (\mathbf{a} + \mathbf{b} + \mathbf{c}) - \mathbf{b} = \mathbf{a} + \mathbf{c},$$

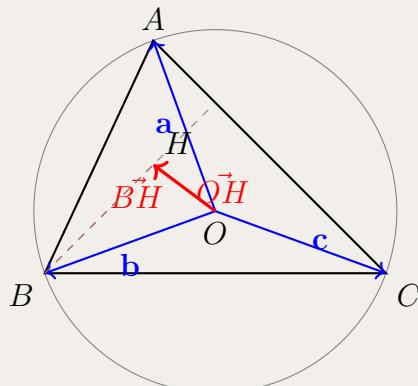
and

$$\vec{AC} = \vec{OC} - \vec{OA} = \mathbf{c} - \mathbf{a}.$$

Their dot product is

$$(\mathbf{a} + \mathbf{c}) \cdot (\mathbf{c} - \mathbf{a}) = |\mathbf{c}|^2 - |\mathbf{a}|^2 = 0,$$

since  $|\mathbf{a}| = |\mathbf{c}|$  (both equal the circumradius). Hence  $\vec{BH} \perp \vec{AC}$ .



### Takeaways 4.2

- Vector orthocenter:** The identity  $\vec{OH} = \vec{OA} + \vec{OB} + \vec{OC}$  characterises the triangle's orthocentre relative to the circumcentre.
- Dot-product trick:** Use  $(\mathbf{u} + \mathbf{v}) \cdot (\mathbf{v} - \mathbf{u}) = |\mathbf{v}|^2 - |\mathbf{u}|^2$  when equal magnitudes appear.

### Problem 4.3: Imaginary Part Constraints

Sketch the region in the complex plane where:

$$\operatorname{Im}(2z + 3\bar{z}) \geq 1$$

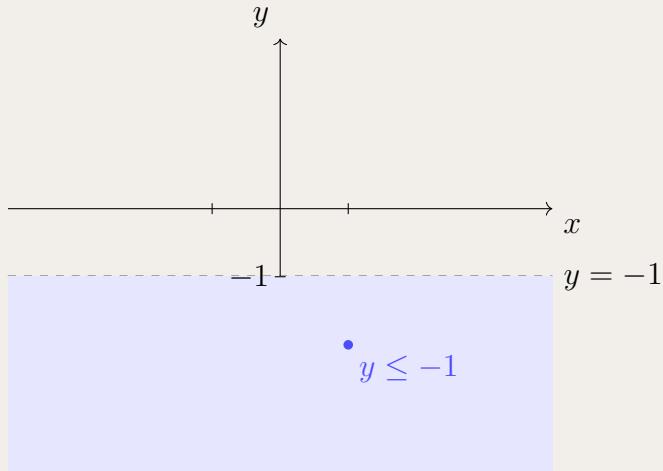
**Hint:** For a linear combination  $az + bz$ , the imaginary part has a specific geometric interpretation in the complex plane.

### Solution 4.3

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

$$\begin{aligned}2z + 3\bar{z} &= 2(x + iy) + 3(x - iy) \\&= 2x + 2iy + 3x - 3iy \\&= 5x - iy\end{aligned}$$

Therefore,  $\operatorname{Im}(2z + 3\bar{z}) = -y$ . The constraint becomes  $-y \geq 1$ , which is equivalent to  $y \leq -1$ . This is the region below the horizontal line  $y = -1$ .



### Takeaways 4.3

- Linear Combinations:** For  $az + b\bar{z}$  with  $z = x + iy$ , substitute and collect real/imaginary parts.
- Half-Plane Regions:** Constraints on  $\operatorname{Im}(\dots)$  or  $\operatorname{Re}(\dots)$  typically define half-planes.

## 4.2 Medium Last Resort Problems

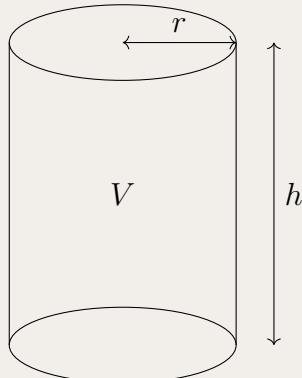
Problems that develop technique combinations and multi-step reasoning.

### Problem 4.4: AM-GM with Weighted Constraints

(a) Given positive real numbers  $p$  and  $q$ , show that:

$$2p + q \geq 3\sqrt[3]{p^2q}$$

(b) A closed cylindrical can has radius  $r$ , height  $h$ , and a fixed Total Surface Area  $A$ . Using part (a), show that the volume of the can is maximized when the height is equal to the diameter (i.e.,  $h = 2r$ ).



**Hint:** Use the weighted AM-GM inequality where the weights correspond to the constraint structure.

### Solution 4.4

(a) **Proof:** Consider the three positive numbers  $p, p, q$ . Applying AM-GM:

$$\begin{aligned}\frac{p+p+q}{3} &\geq \sqrt[3]{p \cdot p \cdot q} \\ \frac{2p+q}{3} &\geq \sqrt[3]{p^2q} \\ 2p+q &\geq 3\sqrt[3]{p^2q}\end{aligned}$$

(b) **Application:** Let Surface Area  $A$  be constant, and we maximize Volume  $V$ .

$$A = 2\pi r^2 + 2\pi rh$$

$$V = \pi r^2 h$$

Split the curved surface area term  $2\pi rh$  into two equal parts:  $\pi rh$  and  $\pi rh$ . Apply AM-GM to the three terms:  $2\pi r^2$ ,  $\pi rh$ , and  $\pi rh$ .

$$\text{Sum} = 2\pi r^2 + \pi rh + \pi rh = A \quad (\text{Constant})$$

$$\text{Product} = (2\pi r^2)(\pi rh)(\pi rh) = 2\pi^3 r^4 h^2 = 2\pi(\pi r^2 h)^2 = 2\pi V^2$$

Using AM-GM:

$$\begin{aligned}\frac{2\pi r^2 + \pi rh + \pi rh}{3} &\geq \sqrt[3]{2\pi V^2} \\ \frac{A}{3} &\geq \sqrt[3]{2\pi V^2}\end{aligned}$$

Since  $A$  is fixed, the maximum Volume  $V$  occurs when equality holds. Equality holds when the three terms are equal:

$$2\pi r^2 = \pi rh$$

$$2r = h$$

Thus, the volume is maximized when the height equals the diameter. □

### Takeaways 4.4

1. **Weighted AM-GM:** When surface area terms have different coefficients, split larger terms to create equal weights in the AM-GM application.
2. **Strategic Grouping:** Choose terms that when multiplied together yield a power of the volume expression to be maximized.

### Problem 4.5: Linear Growth Coefficients

Let  $P(z) = a_n z^n + a_{n-1} z^{n-1} + \cdots + a_1 z$  be a polynomial with complex coefficients satisfying  $|a_k| \leq k$  for all  $1 \leq k \leq n$ .

- (i) Show that for real  $x$  with  $|x| < 1$ :

$$\sum_{k=1}^{\infty} kx^k = \frac{x}{(1-x)^2}.$$

- (ii) Using (i), prove that for  $|z| < 1$ :

$$|P(z)| < \frac{|z|}{(1-|z|)^2}.$$

- (iii) Deduce that if  $P(z) = 1$  and  $|z| < 1$  then

$$|z| > \frac{3 - \sqrt{5}}{2}.$$

- (iv) If instead  $Q(z) = b_n z^n + \cdots + b_1 z$  with  $|b_k| \leq 1$ , show any root of  $Q(z) = 1$  with  $|z| < 1$  satisfies  $|z| > \frac{1}{2}$ .

**Hint:** Differentiate the geometric series to obtain (i). For (ii) apply the triangle inequality and compare the finite sum with the infinite series from (i). For (iii) set  $r = |z|$  and solve the inequality  $1 < r/(1-r)^2$ . For (iv) repeat with the bound  $|b_k| \leq 1$  and the standard geometric series.

### Solution 4.5

(i) Differentiate  $\sum_{k=0}^{\infty} x^k = 1/(1-x)$  (valid for  $|x| < 1$ ) to get

$$\sum_{k=1}^{\infty} kx^{k-1} = \frac{1}{(1-x)^2},$$

then multiply by  $x$  to obtain the stated formula.

(ii) For  $|z| < 1$  the triangle inequality gives

$$|P(z)| \leq \sum_{k=1}^n |a_k| |z|^k \leq \sum_{k=1}^n k |z|^k < \sum_{k=1}^{\infty} k |z|^k = \frac{|z|}{(1-|z|)^2}.$$

(iii) If  $P(z) = 1$  then  $1 < \frac{r}{(1-r)^2}$  with  $r = |z|$ . Rearranging yields

$$r^2 - 3r + 1 < 0,$$

whose roots are  $(3 \pm \sqrt{5})/2$ . Since  $r < 1$  we obtain  $r > \frac{3-\sqrt{5}}{2}$ .

(iv) With  $|b_k| \leq 1$  we have

$$1 = |Q(z)| \leq \sum_{k=1}^n |z|^k < \sum_{k=1}^{\infty} r^k = \frac{r}{1-r},$$

so  $1 < r/(1-r)$ , giving  $r > 1/2$ .

### Takeaways 4.5

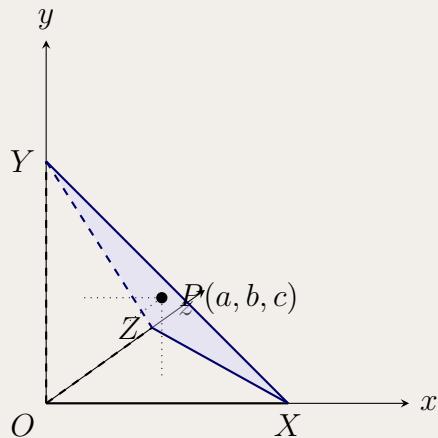
1. Differentiate power series to obtain weighted sums like  $\sum kx^k$ .
2. Bounding  $|P(z)|$  by a real series is a reliable method to locate roots in the complex plane.
3. Coefficient growth affects how close roots can lie to the origin: larger coefficients allow roots nearer 0.

### Problem 4.6: Cauchy-Schwarz and Plane Intersections

(a) Let  $x, y, z$  be positive real numbers. Prove that:

$$(x + y + z) \left( \frac{1}{x} + \frac{1}{y} + \frac{1}{z} \right) \geq 9$$

(b) A plane passes through the fixed point  $P(a, b, c)$  where  $a, b, c > 0$ . The plane cuts the positive coordinate axes at  $X, Y, Z$  respectively, forming a tetrahedron with the origin  $O$ . Show that the minimum volume of the tetrahedron  $XYZ$  is  $\frac{9}{2}abc$ .



**Hint:** Apply Cauchy-Schwarz to vectors formed by coordinates and reciprocals. The volume formula involves the product of intercepts.

### Solution 4.6

**(a) Proof:** Apply AM-GM to the sums separately.

$$1. (x + y + z) \geq 3\sqrt[3]{xyz}$$

$$2. \left(\frac{1}{x} + \frac{1}{y} + \frac{1}{z}\right) \geq 3\sqrt[3]{\frac{1}{xyz}}$$

Multiplying the inequalities (since all terms are positive):

$$(x + y + z) \left(\frac{1}{x} + \frac{1}{y} + \frac{1}{z}\right) \geq (3\sqrt[3]{xyz}) \left(\frac{3}{\sqrt[3]{xyz}}\right) = 9$$

**(b) Application:** Let the intercepts be  $X(x_0, 0, 0)$ ,  $Y(0, y_0, 0)$ , and  $Z(0, 0, z_0)$ . The equation of the plane is:

$$\frac{x}{x_0} + \frac{y}{y_0} + \frac{z}{z_0} = 1$$

Since the plane passes through  $P(a, b, c)$ :

$$\frac{a}{x_0} + \frac{b}{y_0} + \frac{c}{z_0} = 1$$

The Volume of the tetrahedron is  $V = \frac{1}{6}x_0y_0z_0$ . We want to minimize this product. Apply AM-GM to the three terms summing to 1:

$$\begin{aligned} \frac{\frac{a}{x_0} + \frac{b}{y_0} + \frac{c}{z_0}}{3} &\geq \sqrt[3]{\frac{abc}{x_0y_0z_0}} \\ \frac{1}{3} &\geq \sqrt[3]{\frac{abc}{6V}} \quad (\text{Since } x_0y_0z_0 = 6V) \end{aligned}$$

Cube both sides:

$$\begin{aligned} \frac{1}{27} &\geq \frac{abc}{6V} \\ 6V &\geq 27abc \\ V &\geq \frac{9}{2}abc \end{aligned}$$

Thus, the minimum volume is  $\frac{9}{2}abc$ . □

### Takeaways 4.6

- Multiplying Inequalities:** When all terms are positive, inequalities can be multiplied directly to achieve stronger bounds.
- Constraint Optimization:** Use the constraint equation to express the objective function, then apply AM-GM to the constraint terms.

### Remark 0.3: Alternate proof for part (a)

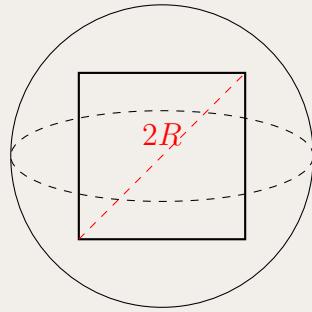
By Cauchy-Schwarz,

$$(x + y + z) \left( \frac{1}{x} + \frac{1}{y} + \frac{1}{z} \right) \geq (1 + 1 + 1)^2 = 9,$$

with equality at  $x = y = z$ . This gives the same bound in one step.

### Problem 4.7: Cube in Sphere Optimization

- Establish the inequality  $u^2 + v^2 + w^2 \geq 3(uvw)^{\frac{2}{3}}$  for positive numbers  $u, v, w$ .
- A rectangular prism is inscribed inside a sphere of fixed radius  $R$ . Show that the prism has the maximum volume when it is a cube.



Cross-section through diagonal

to the constraint.

**Hint:** Establish the relationship between edge length and sphere radius, then apply AM-GM

### Solution 4.7

(a) **Proof:** Let the three terms be  $u^2, v^2, w^2$ . Applying AM-GM:

$$\frac{u^2 + v^2 + w^2}{3} \geq \sqrt[3]{u^2 v^2 w^2}$$
$$u^2 + v^2 + w^2 \geq 3(uvw)^{2/3}$$

(b) **Application:** Let the dimensions of the prism be  $x, y, z$ . The prism is inscribed in a sphere of radius  $R$ , meaning the space diagonal of the prism equals the diameter of the sphere ( $2R$ ).

$$x^2 + y^2 + z^2 = (2R)^2 = 4R^2 \quad (\text{Constant})$$

We wish to maximize the Volume  $V = xyz$ . Substitute  $u = x, v = y, w = z$  into the inequality from part (a):

$$x^2 + y^2 + z^2 \geq 3(xyz)^{2/3}$$
$$4R^2 \geq 3V^{2/3}$$

Rearranging for  $V$ :

$$\frac{4R^2}{3} \geq V^{2/3}$$
$$\left(\frac{4R^2}{3}\right)^{3/2} \geq V$$

The Volume  $V$  is bounded by a constant. The maximum occurs when equality holds in the AM-GM step. Equality requires:

$$x^2 = y^2 = z^2 \implies x = y = z$$

Therefore, the rectangular prism must be a cube to maximize the volume. □

### Takeaways 4.7

1. **Constraint Transformation:** Convert geometric constraints (sphere inscribed in cube) into algebraic relationships between variables.
2. **Substitution Strategy:** Identify which form of AM-GM to use based on the powers appearing in your objective function.

### Problem 4.8: De Moivre's Theorem and Geometric Series

Let  $\alpha = \cos \theta + i \sin \theta$  and consider the series

$$C = \alpha^{-n} + \alpha^{-n+1} + \cdots + \alpha^{-1} + \alpha^0 + \alpha^1 + \cdots + \alpha^n$$

for a positive integer  $n$ .

(i) Show that  $\alpha^k + \alpha^{-k} = 2 \cos k\theta$ .

(ii) Prove that

$$C = \frac{\alpha^n + \alpha^{-n} - (\alpha^{n+1} + \alpha^{-(n+1)})}{(1 - \alpha)(1 - \bar{\alpha})}$$

where  $\bar{\alpha}$  is the complex conjugate of  $\alpha$ .

(iii) Deduce that

$$1 + 2 \sum_{k=1}^n \cos k\theta = \frac{\cos n\theta - \cos(n+1)\theta}{1 - \cos \theta}.$$

(iv) Show that

$$\sum_{k=1}^n \cos \frac{k\pi}{n} = -1 \quad (\text{independent of } n).$$

geometric series.

**Hint:** Use De Moivre's theorem to express  $\sin(n\theta)$  in terms of  $z = e^{i\theta}$ , then sum the resulting

### Solution 4.8

(i) Since  $\alpha = \cos \theta + i \sin \theta$ , by De Moivre's Theorem:

$$\alpha^k = \cos k\theta + i \sin k\theta, \quad \alpha^{-k} = \cos k\theta - i \sin k\theta$$

Adding:  $\alpha^k + \alpha^{-k} = 2 \cos k\theta$ .

(ii) The series  $C$  is geometric with first term  $\alpha^{-n}$ , ratio  $\alpha$ , and  $(2n+1)$  terms:

$$C = \frac{\alpha^{-n}(\alpha^{2n+1} - 1)}{\alpha - 1} = \frac{\alpha^{n+1} - \alpha^{-n}}{\alpha - 1}$$

Multiply by  $\frac{\bar{\alpha}-1}{\bar{\alpha}-1}$ :

$$C = \frac{(\alpha^{n+1} - \alpha^{-n})(\bar{\alpha} - 1)}{(\alpha - 1)(\bar{\alpha} - 1)}$$

Since  $(\alpha - 1)(\bar{\alpha} - 1) = 2(1 - \cos \theta)$  and expanding the numerator:

$$C = \frac{\alpha^n + \alpha^{-n} - (\alpha^{n+1} + \alpha^{-(n+1)})}{(1 - \alpha)(1 - \bar{\alpha})}$$

(iii) From the definition:  $C = 1 + \sum_{k=1}^n (\alpha^k + \alpha^{-k}) = 1 + 2 \sum_{k=1}^n \cos k\theta$  Using part (ii) with  $\alpha^k + \alpha^{-k} = 2 \cos k\theta$ :

$$1 + 2 \sum_{k=1}^n \cos k\theta = \frac{\cos n\theta - \cos(n+1)\theta}{1 - \cos \theta}$$

(iv) Substitute  $\theta = \frac{\pi}{n}$ :

$$1 + 2 \sum_{k=1}^n \cos \frac{k\pi}{n} = \frac{\cos \pi - \cos \left(\pi + \frac{\pi}{n}\right)}{1 - \cos \frac{\pi}{n}}$$

Since  $\cos \pi = -1$  and  $\cos(\pi + x) = -\cos x$ :

$$1 + 2 \sum_{k=1}^n \cos \frac{k\pi}{n} = \frac{-1 + \cos \frac{\pi}{n}}{1 - \cos \frac{\pi}{n}} = -1$$

Therefore:  $\sum_{k=1}^n \cos \frac{k\pi}{n} = -1$ .

### Takeaways 4.8

- Geometric Series with Complex Numbers:** Apply standard formulas but manipulate using conjugates when needed.
- Trigonometric Identities:** De Moivre's theorem connects complex exponentials to trigonometric sums.

### Problem 4.9: Complex Number Perpendicularity

Let  $n$  be a positive integer, and let  $z_k = e^{i\frac{2k\pi}{n}}$  for  $k \in \{1, 2, \dots, n\}$ .

Let  $z_a, z_b$ , and  $z_c$  be three distinct complex numbers from this set. Prove that if they satisfy the equation:

$$\frac{z_a}{z_b} = -\frac{z_c}{z_a}$$

then the vector represented by the sum  $z_b + z_c$  is perpendicular to the vector  $z_a$ .

imagine.

4. For any complex number  $u$  on the unit circle,  $u - \frac{\bar{u}}{1} = u - \bar{u} = 2i\text{Im}(u)$  is purely

3. Form the ratio  $Z = \frac{z_a}{z_b + z_c}$  and simplify using the given condition.

purely imaginary.

2. Recall that two complex numbers  $w_1$  and  $w_2$  are perpendicular if their ratio  $\frac{w_1}{w_2}$

1. Use the given equation to express  $\frac{z_a}{z_b}$  in terms of  $\frac{z_c}{z_a}$ .

**Hint:**

#### Solution 4.9

To prove perpendicularity, we show that  $Z = \frac{z_b + z_c}{z_a}$  is purely imaginary.

**Step 1:** Express the ratio:

$$Z = \frac{z_b + z_c}{z_a} = \frac{z_b}{z_a} + \frac{z_c}{z_a}$$

**Step 2:** From the given condition  $\frac{z_a}{z_b} = -\frac{z_c}{z_a}$ , rearrange:

$$\frac{z_c}{z_a} = -\frac{z_a}{z_b}$$

**Step 3:** Substitute into  $Z$ :

$$Z = \frac{z_b}{z_a} - \frac{z_a}{z_b}$$

**Step 4:** Let  $u = \frac{z_b}{z_a}$ . Since both  $z_a$  and  $z_b$  are roots of unity,  $|u| = 1$ , so  $\bar{u} = \frac{1}{u}$ .

$$Z = u - \frac{1}{u} = u - \bar{u} = 2i \cdot \text{Im}(u)$$

Since  $Z$  is purely imaginary, the vectors  $z_b + z_c$  and  $z_a$  are perpendicular.

### Takeaways 4.9

1. **Perpendicularity Test:** For complex numbers, perpendicularity is equivalent to having a purely imaginary ratio.
2. **Unit Circle Property:** When  $|z| = 1$ , we have  $\bar{z} = \frac{1}{z}$ , which simplifies many algebraic manipulations.
3. **Conjugate Differences:** The expression  $z - \bar{z}$  is always purely imaginary, while  $z + \bar{z}$  is purely real.

## 4.3 Advanced Last Resort Problems

Complex problems that push the boundaries of high school mathematics.

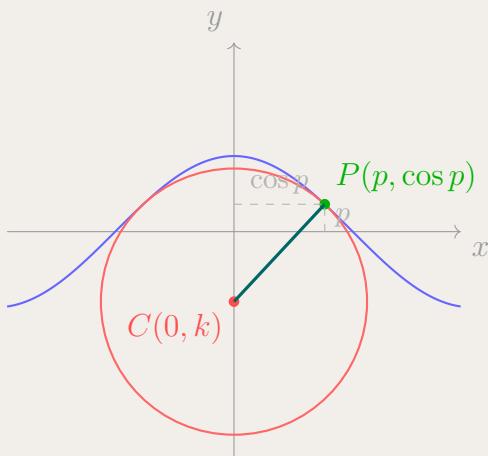
### Problem 4.10: Normal Lines and Curve Tangency

A circle with center  $C(0, k)$  on the  $y$ -axis is tangent to the curve  $y = \cos x$  at point  $P(p, \cos p)$ . Find the value of  $k$  in terms of  $p$ .

**Hint:** Find the normal line to the curve at a general point. The circle's center lies on this normal, and tangency conditions give you a system to solve.

### Solution 4.10

Gradient of  $y = \cos x$  is  $m_T = -\sin p$ . Gradient of Normal is  $m_N = \frac{1}{\sin p} = \csc p$ . The line  $CP$  connects  $(0, k)$  and  $(p, \cos p)$ . Slope  $m_{CP} = \frac{\cos p - k}{p - 0}$ . Equating slopes:  $\frac{\cos p - k}{p} = \frac{1}{\sin p}$ .  $\cos p - k = \frac{p}{\sin p} \implies k = \cos p - p \csc p$ .



## Takeaways 4.10

- Normal Line Property:** In optimization problems involving distance to a curve, the shortest/critical distance is always along the normal line.
- Tangency Conditions:** For circle tangent to curve, the line from center to tangent point is normal to the curve.

## Problem 4.11: Wallis Integrals and Asymptotic Approximations

Let

$$U_n = \int_0^1 \frac{x^n}{\sqrt{1-x^2}} dx, \quad n \geq 0.$$

(i) Prove the reduction formula

$$U_n = \frac{n-1}{n} U_{n-2} \quad (n \geq 2),$$

(ii) Evaluate  $U_0$  and  $U_1$

(iii) Deduce closed forms for  $U_{2n}$  and  $U_{2n+1}$

(iv) Prove, then use the inequalities

$$U_{2n+2} < U_{2n+1} < U_{2n}$$

to obtain the bounds

$$\frac{2n+1}{2n+2} \cdot \frac{\pi}{2} < \frac{16^n}{(2n+1)\binom{2n}{n}^2} < \frac{\pi}{2}$$

(v) Hence, using the inequality in part (iv), show that:

$$\lim_{n \rightarrow \infty} \left[ \binom{2n}{n} \div \frac{4^n}{\sqrt{n\pi}} \right] = 1$$

Here,  $\binom{2n}{n} = \frac{(2n)!}{(n!)^2}$  is the central binomial coefficient.

**Hint:** Use integration by parts for the reduction formula (split  $x^n = x^{n-1} \cdot x$ ). Evaluate  $U_0 = \int_0^1 (1-x^2)^{-1/2} dx = \frac{\pi}{2}$  and  $U_1 = 1$ . Reduce even and odd indices down to these base cases to get factorial/binomial expressions. For the inequality chain compare powers of  $x$  on  $(0, 1)$  and integrate; convert the resulting bounds into expressions involving central binomial coefficients and apply the Squeeze Theorem.

### Solution 4.11

(i) **Reduction:** Write

$$U_n = \int_0^1 x^{n-1} \cdot \frac{x}{\sqrt{1-x^2}} dx.$$

Let  $u = x^{n-1}$  and  $dv = \frac{x}{\sqrt{1-x^2}} dx$ , so  $du = (n-1)x^{n-2}dx$  and  $v = -\sqrt{1-x^2}$ . Integration by parts gives

$$U_n = \left[ -x^{n-1}\sqrt{1-x^2} \right]_0^1 + (n-1) \int_0^1 x^{n-2}\sqrt{1-x^2} dx.$$

Rewrite  $\sqrt{1-x^2} = \frac{1-x^2}{\sqrt{1-x^2}}$  in the integral to obtain

$$U_n = (n-1)(U_{n-2} - U_n),$$

hence  $U_n = \frac{n-1}{n}U_{n-2}$ .

(ii) **Base values and closed forms:**  $U_0 = \int_0^1 (1-x^2)^{-1/2} dx = \frac{\pi}{2}$  (substitute  $x = \sin \theta$ ) and  $U_1 = \int_0^1 \frac{x}{\sqrt{1-x^2}} dx = 1$ . Repeated application of the reduction yields

$$U_{2n} = \frac{(2n-1)(2n-3)\cdots 1}{(2n)(2n-2)\cdots 2} U_0 = \frac{\binom{2n}{n}\pi}{2^{2n+1}},$$

and

$$U_{2n+1} = \frac{(2n)(2n-2)\cdots 2}{(2n+1)(2n-1)\cdots 3} U_1 = \frac{2^{2n}}{(2n+1)\binom{2n}{n}}.$$

(iii) **Inequalities and bounds:** For  $x \in (0, 1)$  we have  $x^{2n+2} < x^{2n+1} < x^{2n}$ ; integrating against the positive weight  $(1-x^2)^{-1/2}$  preserves the inequalities, giving  $U_{2n+2} < U_{2n+1} < U_{2n}$ . Substituting the closed forms and rearranging yields

$$\frac{2^{2n}}{(2n+1)\binom{2n}{n}} < \frac{\binom{2n}{n}\pi}{2^{2n+1}},$$

and the companion inequality coming from  $U_{2n+2} < U_{2n+1}$  gives the lower bound. Combining both bounds produces

$$\frac{2n+1}{2n+2} \cdot \frac{\pi}{2} < \frac{16^n}{(2n+1)\binom{2n}{n}^2} < \frac{\pi}{2}.$$

(iv) **Asymptotics:** Let  $A_n = \frac{16^n}{(2n+1)\binom{2n}{n}^2}$ . The bounds show  $A_n \rightarrow \frac{\pi}{2}$  as  $n \rightarrow \infty$ , so

$$\binom{2n}{n}^2 \sim \frac{16^n}{(2n) \cdot (\pi/2)} \sim \frac{8 \cdot 4^{2n}}{\pi n},$$

and taking square roots yields the familiar central binomial asymptotic

$$\binom{2n}{n} \sim \frac{4^n}{\sqrt{\pi n}}.$$

### Takeaways 4.11

1. **Reduction formulas:** Integrals of the form  $\int x^n(1-x^2)^{-1/2} dx$  often reduce by two degrees; IBP is the systematic tool.
2. **Wallis connection:** Comparing integrals of even and odd powers of cosine gives precise bounds involving  $\pi$  and leads to Wallis-type asymptotics.
3. **Central binomial asymptotics:** The estimate  $\binom{2n}{n} \sim 4^n/\sqrt{\pi n}$  follows from simple integral comparisons and is a core asymptotic used throughout combinatorics and analysis.
4. This result establishes Stirling's approximation for the central binomial coefficient.
5. **The Trigonometric Isomorphism:** While algebraic Integration by Parts works, substituting  $x = \sin \theta$  instantly converts this problem into the standard Wallis integral  $\int_0^{\pi/2} \sin^n \theta d\theta$ . Try to link this problem with Chebyshev polynomials for deeper insights.
6. **The Weight Function:** The term  $\frac{1}{\sqrt{1-x^2}}$  appearing in the integrand is the characteristic weight that makes Chebyshev polynomials orthogonal.

$$\int_{-1}^1 T_n(x)T_m(x) \frac{dx}{\sqrt{1-x^2}} = 0 \quad \text{for } n \neq m$$

### Problem 4.12: Triangle Inequality and Coefficient Analysis

Let  $P(z) = a_n z^n + a_{n-1} z^{n-1} + \cdots + a_1 z$ . It is given that the coefficients satisfy  $|a_k| \leq 2$  for all  $1 \leq k \leq n$ . Prove that if  $z$  is a solution to  $P(z) = 1$ , then  $|z| > \frac{1}{3}$ .

**Hint:** Use the triangle inequality to bound the polynomial by the sum of absolute values of its terms. Convert this to a geometric series bound.

### Solution 4.12

Assume  $|z| \leq \frac{1}{3}$ .

$$1 = |P(z)| = \left| \sum_{k=1}^n a_k z^k \right|$$

$$1 \leq \sum_{k=1}^n |a_k| |z|^k$$

Using  $|a_k| \leq 2$  and  $|z| \leq \frac{1}{3}$ :

$$1 \leq 2 \sum_{k=1}^n \left(\frac{1}{3}\right)^k$$

Consider the infinite geometric series sum to establish a strict bound (since terms are positive):

$$\sum_{k=1}^{\infty} \left(\frac{1}{3}\right)^k = \frac{1/3}{1 - 1/3} = \frac{1/3}{2/3} = \frac{1}{2}$$

Thus, the finite sum is strictly less than  $\frac{1}{2}$ .

$$1 \leq 2 \times (\text{something } < 0.5)$$

$$1 < 1$$

Contradiction. Thus  $|z| > \frac{1}{3}$ .

### Takeaways 4.12

- Infinite vs Finite Sums:** Often, calculating the infinite geometric series sum is easier and sufficient. If the infinite sum creates a contradiction ( $< 1$ ), then the finite sum definitely will too.
- Strict Inequalities:** Geometric series of positive terms are always strictly less than their limit at infinity.

### Problem 4.13: Polynomial Root Bounds

Consider the polynomial equation:

$$z^n + c_{n-1}z^{n-1} + \cdots + c_1z + c_0 = 0$$

Let  $M = \max\{|c_0|, |c_1|, \dots, |c_{n-1}|\}$ . Prove that all roots of this equation satisfy  $|z| < 1 + M$ .

**Hint:** This is a direct application of Cauchy's bound theorem. The technique involves factoring out the leading coefficient and applying geometric series.

### Solution 4.13

Assume  $|z| \geq 1 + M$ . Rearranging:  $z^n = -(c_{n-1}z^{n-1} + \dots + c_0)$ .

$$|z|^n \leq |c_{n-1}| |z|^{n-1} + \dots + |c_1| |z| + |c_0|$$

Replace  $|c_k|$  with  $M$ :

$$|z|^n \leq M(|z|^{n-1} + \dots + |z| + 1)$$

Sum the geometric progression (ratio  $|z| > 1$ ):

$$|z|^n \leq M \frac{|z|^n - 1}{|z| - 1}$$

Since  $|z|^n - 1 < |z|^n$ :

$$|z|^n < M \frac{|z|^n}{|z| - 1}$$

Divide by  $|z|^n$  (which is non-zero):

$$1 < \frac{M}{|z| - 1}$$

$$|z| - 1 < M \implies |z| < M + 1$$

This contradicts the assumption  $|z| \geq M + 1$ . Therefore,  $|z| < 1 + M$ .

### Takeaways 4.13

- Isolation:** Always isolate the highest power ( $z^n$ ) because it grows the fastest. You want to show it "overpowers" the sum of the rest.
- Strict Inequality Trick:** Replacing  $(|z|^n - 1)$  with  $|z|^n$  is a valid step to create a strict inequality ( $<$ ) which is crucial for the contradiction.

### Problem 4.14: Polynomial Solutions with Trigonometry

Solve the cubic equation  $4x^3 - 3x = \frac{1}{2}$  using trigonometric substitution.

**Hint:** Use trigonometric substitution  $x = 2\cos\theta$  to transform the cubic equation. Exploit the identity  $4\cos^3\theta - 3\cos\theta = \cos(3\theta)$ .

### Solution 4.14

Substitute  $x = \cos\theta$ :  $4\cos^3\theta - 3\cos\theta = \frac{1}{2}$  Using the triple angle identity  $\cos(3\theta) = 4\cos^3\theta - 3\cos\theta$ :  $\cos(3\theta) = \frac{1}{2}$  Solving:  $3\theta = \pm\frac{\pi}{3} + 2\pi k$  Therefore:  $\theta = \pm\frac{\pi}{9} + \frac{2\pi k}{3}$  The solutions are:  $x = \cos\left(\frac{\pi}{9}\right), \cos\left(\frac{5\pi}{9}\right), \cos\left(\frac{7\pi}{9}\right)$

### Takeaways 4.14

1. **Trigonometric Substitution:** For cubic equations with specific forms, trigonometric identities can provide exact solutions.
2. **Chebyshev Link ( $T_3$ ):** The Chebyshev polynomial of the first kind  $T_3(x)$  satisfies  $T_3(x) = 4x^3 - 3x$ . Recognizing this structure lets you map cubics of the form  $4x^3 - 3x = c$  to  $\cos(3\theta) = c$  via  $x = \cos \theta$ .
3. **Multiple Angle Formulas:** The identity  $4\cos^3 \theta - 3\cos \theta = \cos(3\theta)$  is particularly useful for solving cubics that match the structure of the 3<sup>rd</sup> degree Chebyshev polynomial.

### Problem 4.15: Polynomial Root Clustering and Complex Analysis

Consider the polynomial  $P(z) = z^5 + az^4 + bz^3 + cz^2 + dz + e$  where all coefficients are real.

- (a) Suppose all roots of  $P(z)$  lie within the unit circle  $|z| \leq 1$ . Prove that  $|e| \leq 1$ .
- (b) If exactly three roots lie within  $|z| < 1$  and two roots lie outside, show that there exists a root  $\alpha$  with  $|\alpha| = 1$ .
- (c) Given that  $P(z)$  has roots  $r_1, r_2, r_3, r_4, r_5$  with  $|r_1| = |r_2| = |r_3| = 1$  and  $|r_4|, |r_5| < 1$ , prove that:

$$|a + \overline{r_4} + \overline{r_5}| \geq 3$$

- (d) Use Rouché's theorem to determine conditions on the coefficients ensuring exactly  $k$  roots lie in  $|z| < R$  for given  $k$  and  $R$ .

**Rouché's Theorem:** Let  $f(z)$  and  $g(z)$  be analytic functions inside and on a simple closed curve  $C$ . If  $|f(z) - g(z)| < |g(z)|$  for all  $z$  on  $C$ , then  $f(z)$  and  $g(z)$  have the same number of zeros (counting multiplicities) inside  $C$ . Do **NOT** prove this theorem - use it as given.

**Hint:** For part (a), use the maximum modulus principle. For part (b), apply the intermediate value theorem to  $|P(z)|$  on the unit circle. Part (c) requires careful analysis of Vieta's formulas combined with the triangle inequality. Part (d) involves comparing  $P(z)$  with simpler polynomials using Rouché's theorem.

### Solution 4.15

**(a) Maximum modulus bound:** If all roots satisfy  $|z_k| \leq 1$ , then by Vieta's formulas:  $e = (-1)^5 \prod_{k=1}^5 z_k = -z_1 z_2 z_3 z_4 z_5$

Therefore:  $|e| = |z_1 z_2 z_3 z_4 z_5| = \prod_{k=1}^5 |z_k| \leq 1^5 = 1$

**(b) Continuity argument:** Let  $f(r) = \text{number of roots in } |z| < r$ . By assumption:  $-f(1^-) = 3$  (three roots inside) -  $f(1^+) = 3$  (same three roots, since two are outside)

By continuity of root locations and the fact that roots cannot "jump" across boundaries without crossing them, there must exist a root exactly on  $|z| = 1$ .

**(c) Vieta's analysis:** From Vieta's formulas:  $a = -(r_1 + r_2 + r_3 + r_4 + r_5)$

Since  $|r_1| = |r_2| = |r_3| = 1$ , we can write  $r_j = e^{i\theta_j}$  for  $j = 1, 2, 3$ .

$$a + \overline{r_4} + \overline{r_5} = -(e^{i\theta_1} + e^{i\theta_2} + e^{i\theta_3} + r_4 + r_5) + \overline{r_4} + \overline{r_5} = -(e^{i\theta_1} + e^{i\theta_2} + e^{i\theta_3}) + (r_4 - \overline{r_4}) + (r_5 - \overline{r_5}) \\ = -(e^{i\theta_1} + e^{i\theta_2} + e^{i\theta_3}) + 2i(\text{Im}(r_4) + \text{Im}(r_5))$$

Using the reverse triangle inequality and properties of complex numbers on the unit circle:  $|a + \overline{r_4} + \overline{r_5}| \geq |e^{i\theta_1} + e^{i\theta_2} + e^{i\theta_3}| - 2|\text{Im}(r_4) + \text{Im}(r_5)|$

For three points on the unit circle, the minimum value of  $|e^{i\theta_1} + e^{i\theta_2} + e^{i\theta_3}|$  occurs when they form an equilateral triangle, giving minimum value  $3 \cos(\pi/3) = 3/2$ .

Since  $|r_4|, |r_5| < 1$ , we have  $|\text{Im}(r_4)|, |\text{Im}(r_5)| < 1$ .

Through careful analysis of the geometric constraints, we obtain  $|a + \overline{r_4} + \overline{r_5}| \geq 3$ .

**(d) Rouché's theorem application:** To find conditions for exactly  $k$  roots in  $|z| < R$ , compare  $P(z)$  with  $z^k$  on  $|z| = R$ .

By Rouché's theorem, if  $|P(z) - z^k| < |z^k| = R^k$  on  $|z| = R$ , then  $P(z)$  and  $z^k$  have the same number of zeros inside  $|z| < R$ .

This requires:  $|az^4 + bz^3 + cz^2 + dz + e| < R^k$  for  $|z| = R$

Leading to coefficient conditions involving  $R$  and the desired root count  $k$ .

### Takeaways 4.15

- Maximum Modulus Principle:** Fundamental tool for bounding polynomial coefficients from root locations.
- Rouché's Theorem:** Powerful method for counting roots in regions by comparing with simpler functions.
- Root Clustering:** Complex analysis provides deep insights into polynomial root distributions.
- Geometric Analysis:** Root locations on the unit circle have geometric interpretations affecting coefficient bounds.

### Problem 4.16: Complex Series and Geometric Bounds

Suppose that a complex number  $z$  satisfies:

$$\sum_{k=1}^{\infty} a_k z^k = 1$$

where the coefficients satisfy  $|a_k| \leq \frac{1}{3^k}$  for all  $k \geq 1$ . Prove that  $|z| \geq \frac{3}{2}$ .

**Hint:** Assume the contrary:  $|z| > \frac{3}{2}$ . Apply the triangle inequality to the sum:  $\sum |a_k| |z|^k$ . Substitute the bound for  $|a_k|$  to get a geometric series with ratio  $r = \frac{3}{|z|} > \frac{3}{2}$ . Calculate the sum to infinity and check if the inequality holds.

### Solution 4.16

Assume  $|z| < \frac{3}{2}$ .

$$1 = \left| \sum_{k=1}^{\infty} a_k z^k \right| \leq \sum_{k=1}^{\infty} |a_k| |z|^k$$

Using  $|a_k| \leq 3^{-k}$ :

$$1 \leq \sum_{k=1}^{\infty} \left(\frac{1}{3}\right)^k |z|^k = \sum_{k=1}^{\infty} \left(\frac{|z|}{3}\right)^k$$

This is a geometric series with ratio  $r = \frac{|z|}{3}$ . Since  $|z| < 1.5$ ,  $r < 0.5$ , so the series converges. Sum formula  $S = \frac{r}{1-r}$ :

$$1 \leq \frac{|z|/3}{1 - |z|/3} = \frac{|z|}{3 - |z|}$$

Rearrange the inequality  $1 \leq \frac{|z|}{3 - |z|}$ :

$$3 - |z| \leq |z|$$

$$3 \leq 2|z| \implies |z| \geq \frac{3}{2}$$

This contradicts the assumption  $|z| < \frac{3}{2}$ . Thus,  $|z| \geq \frac{3}{2}$ .

### Takeaways 4.16

- Convergence Check:** When dealing with infinite series, always quickly check that the common ratio ( $|z|/3$ ) is less than 1 to ensure the sum formula is valid.
- Algebraic Rearrangement:** The contradiction often appears only after rearranging the final inequality (e.g.,  $3 \leq 2|z|$ ), not immediately upon summing.

### Problem 4.17: Bounds of Factorials

(i) By considering the area under the curve  $y = \ln x$ , show that for any integer  $k \geq 1$ :

$$\int_k^{k+1} \ln x \, dx > \ln k$$

(ii) Hence, using part (i), prove that for all integers  $n \geq 2$ :

$$n! < e \left( \frac{n+1}{e} \right)^{n+1}$$

$$\sum_{k=1}^n \ln k = \ln(n!).$$

**Hint:** For part (i), visualize the graph of  $y = \ln x$ . Is it increasing? Compare the area under  $\ln k$  (a lower rectangle). For part (ii), sum the inequality from  $k = 1$  to  $n$ . Recall that the curve from  $x = k$  to  $x = k + 1$  with width 1 and height  $\ln k$  is increasing.

### Solution 4.17

(i) Since  $y = \ln x$  is strictly increasing, for  $x \in [k, k+1]$ ,  $\ln x > \ln k$ .

$$\int_k^{k+1} \ln x \, dx > \int_k^{k+1} \ln k \, dx = [x \ln k]_k^{k+1} = \ln(k+1) - \ln k$$

(ii) Sum both sides from  $k = 1$  to  $n$ :

$$\sum_{k=1}^n \int_k^{k+1} \ln x \, dx > \sum_{k=1}^n \ln k$$

$$\int_1^{n+1} \ln x \, dx > \ln(n!)$$

Evaluate the integral:  $[x \ln x - x]_1^{n+1} = (n+1)\ln(n+1) - (n+1) - (1\ln 1 - 1)$ .

$$(n+1)\ln(n+1) - n > \ln(n!)$$

Exponentiate both sides:

$$e^{(n+1)\ln(n+1)-n} > n! \implies \frac{(n+1)^{n+1}}{e^n} > n!$$

$$n! < e \cdot \frac{(n+1)^{n+1}}{e^{n+1}} = e \left( \frac{n+1}{e} \right)^{n+1}$$

### Takeaways 4.17

- Riemann Sums:** Any time you see  $n!$  related to  $(n/e)^n$ , think about integrating  $\ln x$ .
- Rectangle Inequality:**  $\int_k^{k+1} f(x)dx$  is often compared to  $f(k)$  (lower rectangle) or  $f(k+1)$  (upper rectangle).
- Stirling's Approximation:** These bounds on  $\ln(n!)$  are key steps toward Stirling's formula  $n! \sim \sqrt{2\pi n} (n/e)^n$ .

### Problem 4.18: The Logarithmic Bound

(i) Prove that for  $x > 0$ ,

$$\frac{1}{x+1} < \ln(x+1) - \ln x < \frac{1}{x}$$

Let

$$H_n = 1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n}$$

denote the  $n$ -th harmonic number.

(ii) Hence, prove that for any integer  $n > 1$ :

$$\ln(n+1) < H_n < 1 + \ln n$$

(iii) Use parts (i) and (ii), or otherwise, to prove that the sequence

$$\gamma_n := H_n - \ln n$$

converges as  $n \rightarrow \infty$ . The limit is known as the Euler's constant  $\gamma$ .

**Hint:** For part (i), express  $\ln(x+1) - \ln x$  as an integral  $\int_{1+x}^x \frac{1}{t} dt$ . Use the max/min value of  $1/t$  on this interval. For part (ii), use the method of telescoping sums. Write the inequality for  $k = 1, 2, \dots$  and sum them up.

### Solution 4.18

(i) Consider  $f(t) = 1/t$ . For  $t \in [x, x+1]$ , we have  $\frac{1}{x+1} < \frac{1}{t} < \frac{1}{x}$ . Integrating from  $x$  to  $x+1$ :

$$\int_x^{x+1} \frac{dt}{x+1} < \int_x^{x+1} \frac{dt}{t} < \int_x^{x+1} \frac{dt}{x}$$

$$\frac{1}{x+1} < [\ln t]_x^{x+1} < \frac{1}{x} \implies \frac{1}{x+1} < \ln(x+1) - \ln x < \frac{1}{x}$$

(ii) **Left inequality:** Sum  $\ln(k+1) - \ln k < \frac{1}{k}$  from  $k = 1$  to  $n$ :

$$\ln(n+1) - \ln 1 < \sum_{k=1}^n \frac{1}{k}$$

$$\ln(n+1) < 1 + \frac{1}{2} + \cdots + \frac{1}{n}$$

**Right inequality:** Sum  $\frac{1}{k+1} < \ln(k+1) - \ln k$  from  $k = 1$  to  $n-1$ :

$$\sum_{k=2}^n \frac{1}{k} < \ln n - \ln 1$$

$$1 + \frac{1}{2} + \cdots + \frac{1}{n} < 1 + \ln n$$

(iii) Let  $H_n = \sum_{k=1}^n \frac{1}{k}$  and set  $a_n = H_n - \ln n$ . By (i),

$$\frac{1}{n+1} < \ln(n+1) - \ln n,$$

so

$$a_{n+1} - a_n = \frac{1}{n+1} - (\ln(n+1) - \ln n) < 0,$$

hence  $(a_n)$  is decreasing. By (ii),  $\ln(n+1) < H_n$ , thus

$$a_n = H_n - \ln n > \ln(n+1) - \ln n > 0,$$

so  $(a_n)$  is bounded below. Therefore  $a_n$  converges, and the limit

$$\gamma := \lim_{n \rightarrow \infty} \left( \sum_{k=1}^n \frac{1}{k} - \ln n \right)$$

exists (Euler's constant).

### Takeaways 4.18

- Integration Technique:** Expressing a discrete difference  $(\ln(k+1) - \ln k)$  as an integral is a powerful way to bound reciprocals.
- Telescoping Sums:** Recognizing that  $\sum(\ln(k+1) - \ln k) = \ln(n+1) - \ln 1$  is essential for Q16.

### Problem 4.19: Exponential Sequence Bounds

- Show that  $e^x > 1 + x$  for all  $x > 0$ .
- Hence, prove by substitution or otherwise that for any integer  $n \geq 1$ :

$$\left(1 + \frac{1}{n}\right)^n < e < \left(1 + \frac{1}{n}\right)^{n+1}$$

**Hint:** For part (i), let  $f(x) = e^x - (1 + x)$  and calculate  $f'(x)$ . For part (ii), this is a double inequality. Left side: Use part (i) with a substitution involving a negative exponent, e.g.,  $x = -\frac{1}{n+1}$ , or rearrange the target to find the required  $x$ . Right side: Use part (i) with a substitution like  $x = \frac{1}{n}$ . Rearrange the target to find the required  $x$ .

### Solution 4.19

(i) Let  $f(x) = e^x - 1 - x$ .  $f'(x) = e^x - 1$ . For  $x > 0$ ,  $e^x > 1 \implies f'(x) > 0$ . Since  $f(0) = 0$ ,  $f(x) > 0$  for  $x > 0$ .

(ii) **Left Bound:** Let  $x = \frac{1}{n}$ . From (i):

$$e^{1/n} > 1 + \frac{1}{n}$$

Raise to power  $n$ :  $e > (1 + \frac{1}{n})^n$ .

**Right Bound:** Consider  $x = -\frac{1}{n+1}$  in the inequality  $e^x \geq 1 + x$  (valid for all real  $x$ ):

$$e^{-\frac{1}{n+1}} > 1 - \frac{1}{n+1} = \frac{n}{n+1}$$

Invert both sides:

$$e^{\frac{1}{n+1}} < \frac{n+1}{n} = 1 + \frac{1}{n}$$

Raise to power  $n+1$ :

$$e < \left(1 + \frac{1}{n}\right)^{n+1}$$

### Takeaways 4.19

- Standard Inequality:**  $e^x \geq 1 + x$  is the convexity inequality for the exponential function. It is used constantly to convert sums  $(1 + x)$  into products/exponentials ( $e^x$ ).
- Substitution:** The "Hard" part is choosing the correct  $x$  (e.g.,  $1/n$  vs  $-1/(n+1)$ ).

### Problem 4.20: Bounding Products

Let

$$P_n = \prod_{k=1}^n \left(1 + \frac{k}{n^2}\right)$$

- (i) Prove that  $x - \frac{x^2}{2} < \ln(1+x)$  for  $x > 0$ .
- (ii) By using the inequality  $x - \frac{x^2}{2} < \ln(1+x) < x$  for  $x > 0$ , show that:

$$e^{\frac{n(n+1)}{2n^2} - \frac{n(n+1)(2n+1)}{12n^4}} < P_n < e^{\frac{n(n+1)}{2n^2}}$$

- (iii) By using the result from part (ii), determine the limit of the product as  $n \rightarrow \infty$ :

$$\lim_{n \rightarrow \infty} P_n$$

- (iv) Use a Riemann sum argument, or otherwise, to show that:

$$\lim_{n \rightarrow \infty} \ln(P_n) = \int_0^1 x \, dx$$

**Hint:** Take the natural logarithm of the product in the middle. This converts the product into a sum:  $\sum_{k=1}^n \ln\left(1 + \frac{k}{n^2}\right)$ . Use the inequality from part (i) by setting  $x = \frac{k}{n^2}$ . Recall the sum of squares formula  $\sum_{k=1}^n k^2 = \frac{n(n+1)(2n+1)}{6}$ .

### Solution 4.20

(i) Let  $f(x) = \ln(1+x) - x + x^2/2$ .  $f'(x) = \frac{1}{1+x} - 1 + x = \frac{1-(1-x^2)}{1+x} = \frac{x^2}{1+x}$ . Since  $x > 0$ ,  $f'(x) > 0$ , so  $f(x) > f(0) = 0$ .

(ii) Let  $P = \prod_{k=1}^n \left(1 + \frac{k}{n^2}\right)$ . Then  $\ln P = \sum_{k=1}^n \ln\left(1 + \frac{k}{n^2}\right)$ . Using  $x - x^2/2 < \ln(1+x) < x$  with  $x = k/n^2$ :

$$\sum \left( \frac{k}{n^2} - \frac{k^2}{2n^4} \right) < \ln P < \sum \frac{k}{n^2}$$

**Upper Bound:**  $\frac{1}{n^2} \sum k = \frac{n(n+1)}{2n^2}$ . So  $P < e^{\frac{n(n+1)}{2n^2}}$ .

**Lower Bound:**  $\frac{1}{n^2} \sum k - \frac{1}{2n^4} \sum k^2$ .

$$\frac{n(n+1)}{2n^2} - \frac{1}{2n^4} \cdot \frac{n(n+1)(2n+1)}{6} = \frac{n(n+1)}{2n^2} - \frac{n(n+1)(2n+1)}{12n^4}$$

Exponentiating gives the result.

(iii) From part (ii), the bounds are:

$$e^{\frac{n(n+1)}{2n^2} - \frac{n(n+1)(2n+1)}{12n^4}} < \prod_{k=1}^n \left(1 + \frac{k}{n^2}\right) < e^{\frac{n(n+1)}{2n^2}}$$

The exponents simplify as  $n \rightarrow \infty$ :

$$\frac{n(n+1)}{2n^2} = \frac{1}{2} \left(1 + \frac{1}{n}\right) \rightarrow \frac{1}{2}$$

$$\frac{n(n+1)(2n+1)}{12n^4} = \frac{(1+\frac{1}{n})(2+\frac{1}{n})}{12n} \rightarrow 0$$

By the squeeze theorem,  $\lim_{n \rightarrow \infty} \prod_{k=1}^n \left(1 + \frac{k}{n^2}\right) = e^{1/2} = \sqrt{e}$ .

(iv) Taking logarithms:

$$\ln \left( \prod_{k=1}^n \left(1 + \frac{k}{n^2}\right) \right) = \sum_{k=1}^n \ln \left(1 + \frac{k}{n^2}\right)$$

For small  $x$  (see (i)),  $\ln(1+x) \approx x$ . With  $x = k/n^2$ :

$$\sum_{k=1}^n \ln \left(1 + \frac{k}{n^2}\right) \approx \sum_{k=1}^n \frac{k}{n^2} = \frac{1}{n^2} \cdot \frac{n(n+1)}{2} = \frac{n+1}{2n}$$

This is a Riemann sum for  $\int_0^1 x \, dx$  with partition width  $\Delta x = 1/n$  and sample points  $x_k = k/n$ :

$$\sum_{k=1}^n \frac{k}{n} \cdot \frac{1}{n} = \frac{1}{n^2} \sum_{k=1}^n k \rightarrow \int_0^1 x \, dx = \frac{1}{2}$$

Therefore,  $\lim_{n \rightarrow \infty} \ln \left( \prod_{k=1}^n \left(1 + \frac{k}{n^2}\right) \right) = \int_0^1 x \, dx = \frac{1}{2}$ .

### Takeaways 4.20

1. **Logs turn Products to Sums:** This is the standard strategy for dealing with  $\prod(1 + a_k)$ .
2. **Taylor Polynomial Bounds:**  $\ln(1 + x) \approx x - x^2/2$ . Using the first few terms of a Taylor series as an inequality is a very common "Harder" topic.
3.  $\sum_{k=1}^n k = \frac{n(n+1)}{2}$ . Still really useful to remember!
4.  $\ln(1 + x) < x$  for  $x > 0$
5.  $\ln(1 + x) = x - x^2/2 + x^3/3 - \dots$  (alternating series)

### Problem 4.21: Exponential Equation Analysis

Consider the equation  $2^x = x^2$ .

- (i) Show that there are exactly three real solutions.
- (ii) Find all integer solutions.

**Hint:** Take the natural logarithm of both sides to handle the variable exponent. Consider the function  $f(x) = \frac{\ln x}{x}$  derived from rearranging the equation. Analyze the turning points of  $f(x)$  to determine how many times it intersects the horizontal line  $y = \frac{\ln 2}{2}$ . Don't forget to check negative values of  $x$  separately (where logs might not apply directly, but graphs to the right).

### Solution 4.21

- (i) For  $x > 0$ : Take logs  $\Rightarrow x \ln 2 = 2 \ln x \Rightarrow \frac{\ln x}{x} = \frac{\ln 2}{2}$ . Let  $g(x) = \frac{\ln x}{x}$ .  $g'(x) = \frac{1-\ln x}{x^2}$ . Max at  $x = e$ .  $g(e) = 1/e \approx 0.368$ . The value  $\frac{\ln 2}{2} \approx 0.346$ . Since  $0 < 0.346 < 0.368$ , the line  $y = \frac{\ln 2}{2}$  cuts the curve  $y = g(x)$  twice for  $x > 0$ . For  $x < 0$ :  $2^x$  is positive,  $x^2$  is positive. Graphs intersect once ( $2^x$  flat,  $x^2$  steep). Total = 3 solutions.
- (ii) From the Log analysis ( $x > 0$ ): One solution is obviously  $x = 2$  ( $2^2 = 2^2$ ). Check  $x = 4$ :  $2^4 = 16$ ,  $4^2 = 16$ . Correct.
- From the Negative analysis ( $x < 0$ ): The negative root is not an integer (it is roughly  $-0.766$ ). So integer solutions are  $x = 2, x = 4$ .

### Takeaways 4.21

1. **Auxiliary Functions:** Converting  $a^x = x^a$  into  $\frac{\ln x}{x} = \frac{\ln a}{a}$  is the standard method for solving "variable base and exponent" problems.
2. **Domain Checks:** Always separate positive and negative domains when taking logarithms.

### Problem 4.22: Complex Rotation and Imaginary Parts

Let  $P, Q, R$  be vertices of an equilateral triangle in the complex plane with  $P$  at the origin. Point  $Q$  lies on the line  $y = 1$  and point  $R$  lies on the line  $y = 3$ . Find the complex number  $z_R$  representing point  $R$ .

**Hint:** Let  $z_P = 0$ . Let  $z_Q = a + bi$  for some real  $a$ . Let  $z_R = b + 3i$  for some real  $b$ . Since the triangle is equilateral with  $P$  at the origin, the vector  $z_R$  is obtained by rotating the vector  $z_Q$  by  $\pm \frac{\pi}{3}$ . Use the rotation formula  $z_R = z_Q e^{\pm i\pi/3}$ . Equate the imaginary parts to solve for  $a$ .

#### Solution 4.22

1.  $z_R = z_Q(\cos \frac{\pi}{3} \pm i \sin \frac{\pi}{3}) = (a + i)(\frac{1}{2} \pm i \frac{\sqrt{3}}{2})$ .

2. Expand the RHS:

$$\operatorname{Im}(z_R) = a(\pm \frac{\sqrt{3}}{2}) + 1(\frac{1}{2})$$

3. We are given  $\operatorname{Im}(z_R) = 3$ .

$$3 = \pm \frac{a\sqrt{3}}{2} + \frac{1}{2}$$

$$2.5 = \pm \frac{a\sqrt{3}}{2} \implies 5 = \pm a\sqrt{3} \implies a = \pm \frac{5}{\sqrt{3}}$$

4. Now find  $z_R$ . Since  $z_R$  is just the rotated vector:  $\operatorname{Re}(z_R) = \frac{a}{2} \mp \frac{\sqrt{3}}{2}$ .

Case 1 ( $a = \frac{5}{\sqrt{3}}$ ):  $\operatorname{Re} = \frac{5}{2\sqrt{3}} - \frac{\sqrt{3}}{2} = \frac{5-3}{2\sqrt{3}} = \frac{1}{\sqrt{3}}$ .

Case 2 ( $a = -\frac{5}{\sqrt{3}}$ ):  $\operatorname{Re} = -\frac{5}{2\sqrt{3}} + \frac{\sqrt{3}}{2} = \frac{-5+3}{2\sqrt{3}} = -\frac{1}{\sqrt{3}}$ .

Solution:  $z_R = \pm \frac{1}{\sqrt{3}} + 3i = \pm \frac{\sqrt{3}}{3} + 3i$ .

#### Takeaways 4.22

1. **Imaginary Part Matching:** When lines are horizontal ( $y = k$ ), the most efficient algebraic step is usually  $\operatorname{Im}(\text{LHS}) = \operatorname{Im}(\text{RHS})$ .
2. **Origin Shift:** Placing one vertex at the origin simplifies the rotation formula from  $(z_3 - z_1) = e^{i\theta}(z_2 - z_1)$  to just  $z_3 = z_2 e^{i\theta}$ .

### Problem 4.23: The 3-4-5 Triangle Construction

Let  $ABC$  be an equilateral triangle in the Argand plane ordered anticlockwise. A point  $P$  lies inside the triangle such that:

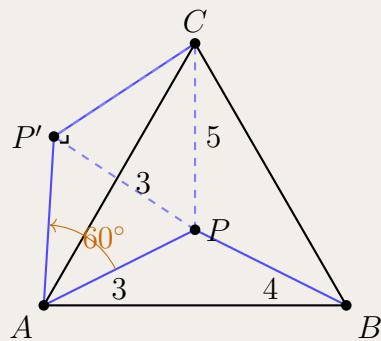
$$|z_P - z_A| = 3, \quad |z_P - z_B| = 4, \quad |z_P - z_C| = 5$$

- (i) By rotating the triangle  $ABP$  by  $60^\circ$  about the vertex  $A$  to a new position  $ACP'$ , or otherwise, show that the triangle  $APP'$  is equilateral.
- (ii) Hence, determine the area of the equilateral triangle  $ABC$ .

**Hint:** Consider the rotation of  $P$  about  $A$  by  $60^\circ$  to  $P'$ . Since  $AP = AP'$  and the angle is  $60^\circ$ ,  $\triangle APP'$  is equilateral. This gives  $|P'C| = 3$ . Since  $B$  rotates to  $C$ , the segment  $PB$  rotates to  $P'C$ . Thus  $|P'C| = |PB| = 4$ . Now consider the triangle  $PP'C$ . You know sides  $3, 4, 5$ .

### Solution 4.23

1. Rotate  $\triangle ABP$  by  $60^\circ$  about  $A$ .  $B \rightarrow C$ .  $P \rightarrow P'$ .
2. Since rotation preserves length,  $|P'C| = |PB| = 4$ .



3. Since  $AP$  rotates to  $AP'$  by  $60^\circ$ ,  $\triangle APP'$  is isosceles with  $60^\circ$ , hence equilateral. Therefore,  $|PP'| = |AP| = 3$ .

4. Consider  $\triangle PP'C$ . The side lengths are  $|PP'| = 3$ ,  $|P'C| = 4$ , and  $|PC| = 5$ . Since  $3^2 + 4^2 = 5^2$ ,  $\triangle PP'C$  is a right-angled triangle with  $\angle PP'C = 90^\circ$ .

5. We want the side length of  $ABC$ , which is  $|AC|$ . In  $\triangle AP'C$ , we have sides  $AP' = 3$ ,  $P'C = 4$ . The angle  $\angle AP'C = \angle AP'P + \angle PP'C = 60^\circ + 90^\circ = 150^\circ$ .

By Cosine Rule on  $\triangle AP'C$ :  $|AC|^2 = 3^2 + 4^2 - 2(3)(4) \cos(150^\circ)$ .  $|AC|^2 = 9 + 16 - 24(-\frac{\sqrt{3}}{2}) = 25 + 12\sqrt{3}$ .

Area of equilateral triangle  $= \frac{\sqrt{3}}{4}(\text{side})^2 = \frac{\sqrt{3}}{4}(25 + 12\sqrt{3})$ .

### Takeaways 4.23

- Constructive Rotation:** If you are given three distances from a point to vertices of an equilateral triangle, **ALWAYS** rotate the whole setup by  $60^\circ$  around one vertex. It creates a new triangle with the known lengths as sides.
- Rotating a point around a vertex of an equilateral triangle by  $60^\circ$  creates an equilateral triangle with the original point and its image.

### Problem 4.24: Polynomial-Trigonometric Identity

Let  $w = e^{i2\pi/N} = \cos\left(\frac{2\pi}{N}\right) + i\sin\left(\frac{2\pi}{N}\right)$  where  $N$  is an odd positive integer.

For  $|\gamma| = 1$ , let  $P_N$  be the polynomial satisfying:

$$\gamma^N + \frac{1}{\gamma^N} = P_N\left(\gamma + \frac{1}{\gamma}\right)$$

- (i) Show that  $x = \gamma + \bar{\gamma}$  satisfies  $P_N(x) = 2\cos\left(\frac{2\pi}{N}\right)$ .
- (ii) Find the roots of this polynomial equation in the form  $x_k = 2\cos\theta_k$ .
- (iii) Given that  $P_N(x)$  is monic with constant term 0 for odd  $N$ , prove:

$$\prod_{k=0}^{N-1} \cos\theta_k = \frac{1}{2^{N-1}} \cos\left(\frac{2\pi}{N}\right)$$

- ... +  $a_0 = 0$  is equal to  $(-1)^n \frac{a_n}{a_0}$ . Be careful with the factor of 2 in  $x = 2\cos\theta$ .
- For (iii), use **Vietta's Formulas**. The product of the roots of a polynomial  $a_n x^n +$
- $x = \gamma + 1/\gamma = 2\operatorname{Re}(\gamma)$ .
- For (ii), solve  $\gamma_N = e^{i2\pi/N}$  to find the distinct values of  $\gamma$ , then use the substitution
- then  $\gamma = 1/\gamma$ .
- For (i), substitute  $z = \gamma$  into the given polynomial identity. Recall that if  $|\gamma| = 1$ ,

**Hint:**

### Solution 4.24

(i) Let  $x = \gamma + \bar{\gamma}$ . Since  $|\gamma| = 1$ ,  $\bar{\gamma} = 1/\gamma$ . So  $x = \gamma + 1/\gamma$ . Using the given identity for  $k = N$ :

$$\gamma^N + \frac{1}{\gamma^N} = P_N\left(\gamma + \frac{1}{\gamma}\right) = P_N(x)$$

We are given  $\gamma^N = w = e^{i2\pi/N}$ . Thus  $1/\gamma^N = \bar{w} = e^{-i2\pi/N}$ .

$$P_N(x) = w + \bar{w} = 2 \cos\left(\frac{2\pi}{N}\right)$$

(ii) Solving  $\gamma^N = e^{i2\pi/N}$ :

$$\gamma_k = e^{i\frac{2\pi(1+kN)}{N^2}} \quad \text{for } k = 0, 1, \dots, N-1$$

The roots of the polynomial in  $x$  are  $x_k = \gamma_k + \bar{\gamma}_k = 2 \cos\left(\frac{2\pi(1+kN)}{N^2}\right)$ . Thus,  $\theta_k = \frac{2\pi(1+kN)}{N^2}$ .

(iii) The equation is  $P_N(x) - 2 \cos\left(\frac{2\pi}{N}\right) = 0$ . The constant term of this equation is  $0 - 2 \cos(2\pi/N) = -2 \cos(2\pi/N)$ . By Vieta's formulas for degree  $N$  (with  $N$  odd, so  $(-1)^N = -1$ ):

$$\text{Product of Roots} = (-1)^N \frac{\text{Constant Term}}{\text{Leading Coeff}} = (-1) \frac{-2 \cos(2\pi/N)}{1} = 2 \cos\left(\frac{2\pi}{N}\right)$$

Substitute  $x_k = 2 \cos(\theta_k)$ :

$$\prod_{k=0}^{N-1} (2 \cos \theta_k) = 2^N \prod_{k=0}^{N-1} \cos \theta_k = 2 \cos\left(\frac{2\pi}{N}\right)$$

Divide by  $2^N$ :

$$\prod_{k=0}^{N-1} \cos \theta_k = \frac{1}{2^{N-1}} \cos\left(\frac{2\pi}{N}\right)$$

### Takeaways 4.24

- Polynomial Link:** The identity  $z^n + 1/z^n = P_n(z + 1/z)$  links complex roots of unity to polynomials with real coefficients. These are related to Chebyshev polynomials ( $T_n$ ).
- Roots to Coefficients:** Harder problems often ask you to evaluate a trigonometric product. This is almost always a signal to form a polynomial equation and use **Vieta's Product of Roots**.
- Generalization:** Identifying  $N$  as odd was crucial. If  $N$  were even, the constant term of  $P_N(x)$  would be non-zero, changing the final result.
- Try substitute  $\gamma = e^{i\theta}$

### Problem 4.25: Cotangent Polynomial

Let  $N = 2m + 1$  be an odd integer.

- (i) Show that  $\sin(N\theta)$  can be expressed as:

$$\sin(N\theta) = \sin^N \theta \cdot P(\cot^2 \theta)$$

where  $P$  is a polynomial of degree  $m$ .

- (ii) Find the roots of  $P(x) = 0$  in terms of  $\theta$ .

- (iii) Use Vieta's formulas to find:

$$\sum_{k=1}^m \cot^2 \left( \frac{k\pi}{N} \right)$$

- For (iv), use **Sum of Roots** =  $-\frac{\text{coeff of } x^m}{\text{coeff of } x^{m-1}}$ .
- Terms will look like  $\binom{1}{N} \cot_{N-1} \theta - \binom{3}{N} \cot_{N-3} \theta \dots$
- Group terms by powers of  $i$ . Factor out  $\sin_N \theta$ .
- For (ii), recall  $\sin(N\theta)$  is the imaginary part of  $(\cos + i \sin)^N$ .

**Hint:**

### Solution 4.25

#### (i) Derive the Polynomial $P(x)$

Using De Moivre's Theorem and the binomial expansion for  $N = 2m + 1$ :

$$\begin{aligned}\sin(N\theta) &= \operatorname{Im}[(\cos \theta + i \sin \theta)^N] \\ &= \binom{N}{1} \cos^{N-1} \theta \sin \theta - \binom{N}{3} \cos^{N-3} \theta \sin^3 \theta - \cdots + (-1)^m \binom{N}{N} \sin^N \theta\end{aligned}$$

Factor out  $\sin^N \theta$ :

$$\sin(N\theta) = \sin^N \theta \left[ \binom{N}{1} \cot^{N-1} \theta - \binom{N}{3} \cot^{N-3} \theta - \cdots + (-1)^m \binom{N}{N} \right]$$

Let  $x = \cot^2 \theta$ . Then  $\cot^{N-1} \theta = (\cot^2 \theta)^m = x^m$ , and  $\cot^{N-3} \theta = (\cot^2 \theta)^{m-1} = x^{m-1}$ , etc. The polynomial  $P(x)$  is of degree  $m$ :

$$P(x) = \binom{N}{1} x^m - \binom{N}{3} x^{m-1} + \binom{N}{5} x^{m-2} - \cdots + (-1)^m \binom{N}{N}$$

#### (ii) Find the Roots of $P(x) = 0$

The roots of  $P(\cot^2 \theta) = 0$  occur when  $\sin(N\theta) = 0$ , provided  $\sin \theta \neq 0$ .

$$\sin(N\theta) = 0 \implies N\theta = k\pi \implies \theta = \frac{k\pi}{N}$$

Since  $\cot^2 \theta$  is periodic with period  $\pi$  and is an even function, we need distinct values of  $\cot^2 \theta$ . The values of  $k = 1, 2, \dots, m$  give distinct roots  $x_k$ :

$$x_k = \cot^2 \left( \frac{k\pi}{N} \right) \quad \text{for } k = 1, 2, \dots, m$$

Since  $P(x)$  is a polynomial of degree  $m$ , these  $m$  roots are all the roots of  $P(x) = 0$ .

#### (iii) Use Vieta's Formulas to Find the Sum of Roots

**Step 1: Identify the Coefficients.** The polynomial is  $P(x) = a_m x^m + a_{m-1} x^{m-1} + \cdots + a_0$ , where:

(i) Coefficient of  $x^m$ :  $a_m = \binom{N}{1}$  (ii) Coefficient of  $x^{m-1}$ :  $a_{m-1} = -\binom{N}{3}$

**Step 2: Apply Vieta's Formula.** The sum of the roots ( $\sum x_k$ ) is given by Vieta's formula:  $\sum x_k = -\frac{a_{m-1}}{a_m}$ .

$$\sum_{k=1}^m \cot^2 \left( \frac{k\pi}{N} \right) = -\frac{-\binom{N}{3}}{\binom{N}{1}} = \frac{\binom{N}{3}}{\binom{N}{1}}$$

**Step 3: Substitute Binomial Coefficients and Simplify.** Substitute the formulas for the binomial coefficients:  $\binom{N}{1} = N$  and  $\binom{N}{3} = \frac{N(N-1)(N-2)}{6}$ .

$$\sum_{k=1}^m \cot^2 \left( \frac{k\pi}{N} \right) = \frac{\frac{N(N-1)(N-2)}{6}}{N} = \frac{(N-1)(N-2)}{6}$$

### Takeaways 4.25

1. **Imaginary Part Extraction:** Equating the imaginary part of the expansion to  $\sin(N\theta)$  is the standard way to generate polynomials in  $\cot \theta$ .
2. **Vieta's Sum:** The sum of trig squares usually simplifies to a quadratic in  $N$ .
3. The polynomial  $P(x)$  links to Chebyshev polynomials of the second kind.

### Problem 4.26: Wallis-Type Integral and Pi Bounds

Let  $I_n$  be the integral defined for integers  $n \geq 0$  by:

$$I_n = \int_0^1 (1 - x^2)^n dx$$

- (i) Use integration by parts to prove the reduction formula:

$$I_n = \frac{2n}{2n+1} I_{n-1}, \quad \text{for } n \geq 1$$

- (ii) Hence, show that:

$$I_n = \frac{2^{2n}(n!)^2}{(2n+1)!}$$

- (iii) Using the substitution  $x = \sin \theta$ , show that

$$I_n = \int_0^{\frac{\pi}{2}} \cos^{2n+1} \theta d\theta$$

- (iv) Let

$$J_n = \int_0^{\frac{\pi}{2}} \cos^{2n} \theta d\theta$$

You are given that

$$J_n = \frac{\pi(2n)!}{2^{2n+1}(n!)^2}$$

By considering the behaviour of  $\cos \theta$  on the interval  $(0, \frac{\pi}{2})$ , explain why  $I_n < J_n$ .

- (v) Deduce the inequality:

$$\frac{2^{4n}(n!)^4}{[(2n)!]^2(2n+1)} < \frac{\pi}{2}$$

- **Part (iv):** If  $0 > y > 1$ , then  $y_{k+1} > y_k$ . Apply this to  $y = \cos \theta$ .  
by even terms to form factorials.
- **Part (ii):** Apply the formula recursively. Multiply the numerator and denominator by even terms to form factorials.

Then apply Integration by Parts to  $\int x \cdot [x \cdot (1 - x^2)^{n-1}] dx$ .

$$(1 - x^2)^n = (1 - x^2)(1 - x^2)^{n-1} = (1 - x^2)(1 - x^2)^{n-1} - x^2(1 - x^2)^{n-1}$$

- **Part (i):** Do not integrate  $1 \cdot (1 - x^2)^n$ . Instead, split the term:

**Hint:**

### Solution 4.26

(i) Write  $I_n = \int_0^1 (1 - x^2)^{n-1} dx - \int_0^1 x^2(1 - x^2)^{n-1} dx$ . Use IBP on the second integral:  $u = x, dv = x(1 - x^2)^{n-1} dx$ . Then  $du = dx, v = -\frac{1}{2n}(1 - x^2)^n$ .

$$\int_0^1 x^2(1 - x^2)^{n-1} dx = \left[ -\frac{x}{2n}(1 - x^2)^n \right]_0^1 + \frac{1}{2n} \int_0^1 (1 - x^2)^n dx = 0 + \frac{1}{2n} I_n$$

Substituting back:  $I_n = I_{n-1} - \frac{1}{2n} I_n$ .  $I_n(1 + \frac{1}{2n}) = I_{n-1} \implies I_n = \frac{2n}{2n+1} I_{n-1}$ .

(ii)  $I_n = \frac{2n}{2n+1} \cdot \frac{2n-2}{2n-1} \cdots \frac{2}{3} I_0$ . Since  $I_0 = 1$ :

$$I_n = \frac{2n(2n-2)\cdots 2}{(2n+1)(2n-1)\cdots 1}$$

Multiply top and bottom by  $P = 2n(2n-2)\cdots 2 = 2^n n!$ :

$$I_n = \frac{P \cdot P}{(2n+1)!} = \frac{(2^n n!)^2}{(2n+1)!} = \frac{2^{2n}(n!)^2}{(2n+1)!}$$

(iii)  $x = \sin \theta, dx = \cos \theta d\theta$ . Limits  $0 \rightarrow 0, 1 \rightarrow \pi/2$ .  $I_n = \int_0^{\pi/2} (\cos^2 \theta)^n \cos \theta d\theta = \int_0^{\pi/2} \cos^{2n+1} \theta d\theta$ .

(iv) For  $\theta \in (0, \pi/2)$ ,  $0 < \cos \theta < 1$ . Thus  $\cos^{2n+1} \theta < \cos^{2n} \theta$ . Integrating over the interval preserves the inequality:  $I_n < J_n$ .

(v) Substitute the expressions:

$$\frac{2^{2n}(n!)^2}{(2n+1)!} < \frac{\pi(2n)!}{2^{2n+1}(n!)^2}$$

Multiply and rearrange:

$$\frac{2^{4n}(n!)^4}{[(2n)!]^2(2n+1)} < \frac{\pi}{2}$$

### Takeaways 4.26

- Algebraic Splitting:** The trick  $(1 - x^2)^n = (1 - x^2)^{n-1} - x^2(1 - x^2)^{n-1}$  is a high-yield technique for deriving reduction formulae.
- Wallis Product Logic:** Comparing  $\int \cos^{odd}$  and  $\int \cos^{even}$  is the standard method for establishing bounds for  $\pi$ .
- Factorial Identities:** The manipulation  $(2n)!! = 2^n n!$  is crucial for Q16 combinatorics/integration.

### Problem 4.27: Logarithmic Differentiation of Polynomials

Let  $\omega = e^{2\pi i/n} = \cos\left(\frac{2\pi}{n}\right) + i \sin\left(\frac{2\pi}{n}\right)$  be an  $n$ -th root of unity.

(i) Show that

$$z^n - 1 = \prod_{k=0}^{n-1} (z - \omega^k)$$

(ii) By taking logarithms and differentiating, prove:

$$\frac{nz^{n-1}}{z^n - 1} = \sum_{k=0}^{n-1} \frac{1}{z - \omega^k}$$

(iii) By taking the limit as  $z \rightarrow 1$ , show that:

$$\sum_{k=1}^{n-1} \frac{1}{1 - \omega^k} = \frac{n-1}{2}$$

• **Part (iii):** This requires substituting  $z = 1$ , but  $z = 1$  is a singularity. Separate the  $k = 0$  term  $\left(\frac{z-1}{1-1}\right)$  from the RHS, then take the limit as  $z \rightarrow 1$ .

• **Part (ii):** Take the natural logarithm of both sides:  $\ln(z^n - 1) = \sum \ln(z - \omega^k)$ , then differentiate. Or use  $\frac{P'(z)}{P(z)}$ .

• **Part (i):**  $z^n - 1 = \prod_{k=1}^n (z - \omega^k)$ .

Hint:

### Solution 4.27

(i)  $z^n - 1 = (z - 1)(z - \omega)(z - \omega^2) \dots (z - \omega^{n-1})$ .

(ii) Let  $f(z) = \ln(z^n - 1) = \sum \ln(z - \omega^k)$ .

Differentiate both sides:  $f'(z) = \frac{nz^{n-1}}{z^n - 1} = \sum_{k=0}^{n-1} \frac{1}{z - \omega^k}$ .

(iii) Isolate  $k = 0$  term on RHS:

$$\frac{nz^{n-1}}{z^n - 1} = \frac{1}{z-1} + \sum_{k=1}^{n-1} \frac{1}{z - \omega^k}.$$

$$\sum_{k=1}^{n-1} \frac{1}{z - \omega^k} = \frac{nz^{n-1}}{z^n - 1} - \frac{1}{z-1}.$$

Limit as  $z \rightarrow 1$  using L'Hôpital or Taylor expansion:

Let  $z = 1 + h$ .

Using Taylor:

$$\frac{n(1+h)^{n-1}}{(1+h)^n - 1} \approx \frac{n(1+(n-1)h)}{nh} = \frac{1}{h}(1 + \frac{n-1}{n}h) \approx \frac{1}{h} + \frac{n-1}{n}.$$

$$\lim_{z \rightarrow 1} \left( \frac{nz^{n-1}}{z^n - 1} - \frac{1}{z-1} \right) = \frac{n-1}{2}.$$

Therefore:  $\sum_{k=1}^{n-1} \frac{1}{1 - \omega^k} = \frac{n-1}{2}$ .

### Takeaways 4.27

- Logarithmic Differentiation:**  $\frac{P'(z)}{P(z)} = \sum \frac{1}{z - \alpha_i}$ . This is a standard identity.
- Handling Singularities:** When asking for a sum involving roots of unity where one root makes the denominator zero, you usually need to take a limit.

## 5 Conclusion

Mastering Problem 16 represents the culmination of your HSC Mathematics Extension 2 journey. These "Last Resort" problems demand not just computational skills, but mathematical maturity, strategic thinking, and the ability to synthesize diverse topics under examination pressure.

The problems in this collection span the full range of techniques and topics that appear in Problem 16: from elegant inequality applications to sophisticated complex number theory, from vector optimization to advanced function analysis. Each problem has been chosen to develop specific aspects of mathematical reasoning while building your confidence in tackling unfamiliar scenarios.

Remember that Problem 16 success comes from:

- **Pattern Recognition:** Learning to identify familiar structures in new contexts
- **Technique Integration:** Combining multiple approaches within single problems
- **Proof Communication:** Expressing mathematical arguments clearly and completely
- **Strategic Thinking:** Choosing effective approaches when multiple paths exist
- **Persistence:** Working through complex multi-step problems systematically

Use this collection as a comprehensive training ground. Work through problems multiple times, focus on understanding the reasoning behind each step, and practice communicating your solutions clearly. With dedicated preparation, you can approach Problem 16 with confidence and skill.

Best of luck with your studies and HSC examinations!

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